no ab

THE

SCIENTIFIC PROCEEDINGS

OF THE

ROYAL DUBLIN SOCIETY

VOL. 25 (N.S.)

No. 20. 12 NOVEMBER, 1951

THE RADIOACTIVITY OF POTASSIUM 40

By C. F. G. DELANEY

DUBLIN :
PUBLISHED BY THE ROYAL DUBLIN SOCIETY,
BALL'S BRIDGE, DUBLIN

1951

Price : Seven Shillings

No. 20

THE RADIOACTIVITY OF POTASSIUM 40.

BY

C. F. G. DELANEY

[Read April 17, 1951. Published November 12, 1951.]

Potassium is one of the few elements of moderate atomic number which are naturally radioactive. This radioactivity has been shown (1) to be due to the K^{40} isotope, which is now known to disintegrate both by beta emission to Ca^{40}, and by K capture (2) followed by gamma emission to A^{40}. The present investigation aims at determining the specific beta activity of ordinary potassium (from which the corresponding decay constants for K^{40} may be deduced) and the maximum energy of the beta particles.

The discussion will be divided into three sections—

1. General method.
2. Particular methods and instruments.
3. Estimation of errors, comparison of results with those obtained by other workers, and survey of proposed decay schemes for K^{40}.

Section 1. General Method.

A Geiger Muller (' G.M.') counter was chosen as the obvious method of detecting the individual electrons from potassium or one of its compounds. Two types are in general use for beta counting—the thin-wall and the end-window type. The primary consideration in this particular problem was always the extremely low activity of potassium compared with, say, members of the Uranium and Thorium series, or with artificial radioisotopes. Consequently it was of vital importance that as large a counter ' geometry ' as possible be used, *i.e.* that as large a fraction as possible of the beta particles leaving a source placed near the counter be recorded. (It seems preferable to use the term ' geometry ' here rather than ' counter efficiency ', the latter being customarily retained to describe the percentage of particles entering the active volume of the counter which initiate a discharge. The efficiency for beta radiation (3) is in most cases very nearly 100 per cent. The geometry, then, refers to that fraction of the total particles which both leave the source so as to enter the counter and produce observable pulses there when they do.)

The thin-wall counter offered the advantage that if a cylindrical coaxial source were placed close to it the geometry would be very nearly 50 per cent. Furthermore,

the actual length of the counter (and therefore of the source) could easily be made say 20 cm., with a consequent improvement in the total count to background ratio. It was also felt that if any calculations on the geometry were being undertaken this configuration would be particularly amenable to such. Two factors, however, militated against the use of such a counter. Firstly, it is hard to turn counter shells down to much below a thickness of 0·1 mm. (27 mg./cm.^{2} of aluminium). Such a shell will stop all beta particles with an energy less than about 160 KEV, and a correction factor of large proportions will have to be introduced to allow for this absorption. Also, it is not easy either to prepare sources in cylindrical form or to insert and hold absorbers of the same shape between source and counter.

On account of these difficulties an end window counter was preferred. In choosing its dimensions a compromise had to be made. It was desirable to make the diameter as large as possible in order that the actual amount of KCl being counted could also be large. Increasing the diameter, however, necessarily implied a mica window of increased thickness, with consequent transmission losses. The values finally adopted were, cathode diameter 5·05 cm. window thickness 9·6 mg/cm.^{2} (*i.e.* just transparent to 82 KEV electrons), and total cathode length 4·8 cm. Actual details of source, mounting, dimensions, etc., are given in Section 2.

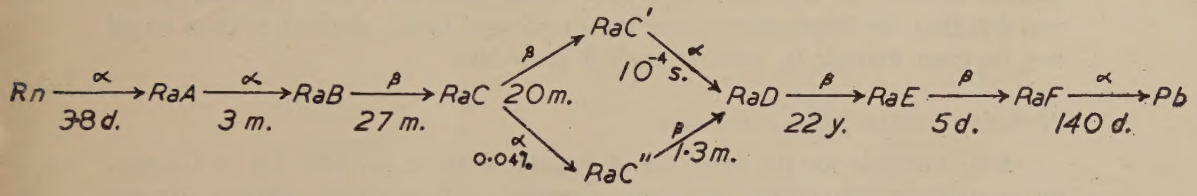
By counting a source of some potassium compound placed close to the counter window a measure of the specific activity could be obtained. This measure can have no absolute significance, however, unless the geometry, as defined previously, has been determined. Before describing how this was done, the choice of a potassium compound most suitable for counting will be discussed. On account of the low activity of potassium it is important that the compound should contain as high a percentage as possible of potassium itself. Metallic potassium and KOH are at once eliminated on account of difficulties of handling. KF, the next choice, was actually tried, but found impracticable owing to its hygroscopic nature, and to the possibility of small quantities of HF being set free. This left KCl as the most suitable remaining compound, and it was found to be very successful in practice and not measurably hygroscopic. The sources were prepared by distributing fine crystalline KCl uniformly over a flat circular nickel container, by means of a shaker.

To return to the question of geometry: Methods are available for absolute counting of alpha particles on account of their greater ionisation, and it is usual in calibration measurements to prepare a standard source containing two elements in a radioactive chain. If one of these elements is alpha active and the other beta active, and the alpha activity of the one is determined absolutely, then the absolute beta activity of the other can be deduced from a knowledge of the decay constant, of the two elements. By comparing this absolute beta activity with the beta activity as measured by the counter, the geometry may be found. Two possible pairs of elements are available—U + UX, and RaE + RaF (polonium). Both combinations have the advantage of emitting practically no gamma rays. One disadvantage of the first pair is at once obvious—each ' element ' is itself complex. True, U(I + II) and UX_2 supply most of the measurable alpha and beta activity, but the corrections

for AcU and its daughter UY are by no means negligible, and it is particularly awkward to have present in the betas the soft component of UX_1 ($E_{max.} \sim 200$ KEV.), some part of which will traverse the counter window unless we are prepared to increase the latter's thickness to beyond 40 mg./cm.^{2} Further, since uranium has a very long half life ($4{\cdot}5 \times 10^9$ yrs.) an appreciable amount of material will have to be used to give a reasonable alpha count. For example, one experimental uranium nitrate source which gave a suitable count was estimated to have a thickness equivalent to about 0·25 cm. of air. Since the range of UI alphas in air is 2·67 cm. this means that those alphas which leave the source at a large angle to the normal will have residual ranges in air so small as to make their detection difficult. As the source was by no means uniformly deposited there may be an even larger error involved.

With Ra(E + F), however, only one beta-emitting body is present, detection of the alpha rays from RaF is easier on account of their longer range (3·87 cm.), and on account of the shorter half lives involved (see below), a sufficiently strong source could be obtained with so small an amount of material that no visible trace was present.

The relevant part of the U series is as follows,



Solutions of Ra(D + E + F) were obtained by digesting one or more old radon tubes in N/10 HCl. Since it was desired to have a favourable RaE/RaF ratio in the final source it was advisable to have tubes of sufficient age compared with the half life of Rn (3·8 days) so that nearly all of this was transformed into RaD (intervening products having very short half lives), and yet not long enough compared with the half life of RaF (140 days) for too much of this to be formed. A tube a few weeks old would be very suitable and would allow a large formation of RaE (half life 5 days) without excessive RaF, and as far as possible tubes of about this age were selected. RaE sources containing some RaF were prepared from a Ra(D + E + F) solution by spontaneous deposition on nickel, the RaD not coming down. Since the amount of RaE present in the source is estimated by the increase in alpha activity of the RaF after deposition, the ideal source would contain as little RaF as possible, in order that the percentage increase in alpha activity would be a maximum. Some preferential removal of the RaF is thus necessary, and was in fact possible by making a number of preliminary depositions at room temperature, since RaF comes down with little RaE in the cold (4).

The RaE is only deposited in appreciable amounts at higher temperatures (~80° C.), but naturally a large part of the remaining RaF comes down as well.

Consequently, the initial ratio of (number of atoms of RaF)/(number of atoms of RaE), for the four sources prepared, worked out at 1·25 (S17), 1·65 (S18), 1·01 (S19), and 1·42 (S20), with corresponding increases in the RaF alpha activity of 61 per cent, 45·5 per cent, 76 per cent, and 53 per cent, over a twenty day period. These values may be compared with the RaF/RaE ratio when these are in quasi-steady equilibrium in old Rn tubes with their fairly long lived parent RaD. Here, (number of atoms of RaF)/(number of atoms of RaE) = (half life of RaF)/(half life of RaE) = 140/5 = 28. With radon tubes of less age this ratio may easily be lower by a factor of two or three, but even so an enrichment factor of about five has been achieved even in the worst case. Also a 45·5 per cent increase in activity permits a reasonably accurate estimate to be made of the amount of RaE present initially. In one respect a moderate initial alpha activity is desirable. If only a small amount of RaF is present originally, from the very nature of the detecting devices used, a large percentage error is involved in its determination. Since it is the increase in alpha activity which is significant, the greater accuracy with which a larger initial amount of RaF may be determined helps to counterbalance the difficulties due to the resultant smaller value of this increase.

Finally, if chemical separation, such as described by Burtt (5), had been employed, undoubtedly a smaller RaF/RaE ration could have been obtained, but it was felt that the improvement over the simple and direct physical method would not be great enough to warrant such a procedure.

Methods of alpha particle detection.

Four methods for the detection of individual alpha particles are in common use :—(1) Ionisation chamber and linear amplifier, (2) Proportional counter, (3) Scintillation methods, and (4) Nuclear plates.

The great advantage of method (4) over the others is that the geometry is known immediately, and is in fact 50 per cent. For the other methods calibration is obtained by placing a weighed amount of some long-lived alpha emitter (such as uranium or plutonium) in a standard position in front of the counter and deducing the geometry from the ratio, (observed count)/(calculated number of disintegrations). The substance must be of long half life in order that a weighable quantity of material may not give an impossibly large number of disintegrations per second : this immediately precludes the possibility of applying this procedure directly to the determination of the beta geometry for G.M. tubes, since no really long lived beta emitter is known. The presence of a macroscopic amount of material entails the inevitable corrections for absorption, with their resultant uncertainty. Neither does the use of a 2π ionisation chamber immediately imply a 50 per cent geometry. On account of noise in the chamber and the subsequent amplifier stages it is necessary to set the bias on the recording equipment to a small, non zero voltage—*i.e.*, adjust it to respond only to signals of voltage greater than the noise level. Consequently, a certain number of pulses (due to alphas which may have taken a long path through the active material or a short path through the chamber) will be of less voltage than the random

noise level, and must inevitably be missed. Either a theoretical correction or a calibration with a weighed source as before, is therefore necessary.

On the contrary, if a source is placed in contact with a nuclear plate, that is a photographic plate sensitive to ionising radiation and in particular to alpha particles, then all particles leaving the source in the 2π solid angle next to the plate will enter the emulsion and be recorded. We have in fact a zero noise level, and the geometry is thus 50 per cent. This statement is, however, subject to the reservation that backscattering should be negligible, *i.e.*, that only a negligible number of alpha particles leaving the source in the 2π solid angle away from the plate will be deflected by multiple scattering back into the emulsion. That this is very nearly so may be seen from tables published by Rossi and Staub (6). For an infinitely thin source (such as the RaF ones used here) on a thick backing, combined with a recording instrument whose efficiency is normally 50 per cent, their formula reads

$$F = \tfrac{1}{2}\ (1 + 0{\cdot}201\ \phi)$$

where F = the fraction of particles leaving the source which are counted, and ϕ = the backscattering factor.

ϕ depends, naturally, on the backing and a table for four elements is shown below :—

	ϕ material/ϕ gold
Gold	1·00
Platinum	0·99
Aluminium	0·23
Beryllium	0·10

These values are shown plotted against atomic weight and atomic number of the material in figs 1 and 2 respectively, in order to estimate ϕ nickel/ϕ gold. It can be seen that unless nickel behaves very anomalously it is unlikely that this ratio is greater than 0·4 for it. Now ϕ gold $= \left(9{\cdot}7 \times 10^{-2}\right) \sqrt{3{\cdot}68/3{\cdot}87}$, the square root factor taking account of the difference in the ranges of the alphas used in the experiments from which these figures are taken and the alphas from RaF.

Hence ϕ nickel $\leqslant 0{\cdot}4 \times 9{\cdot}7 \times 10^{-2} \sqrt{3{\cdot}68/3{\cdot}87}$

and $F \leqslant \tfrac{1}{2}(1 + 0{\cdot}201 \times 0{\cdot}4 \times 9{\cdot}7 \times 10^{-2} \sqrt{3{\cdot}68/3{\cdot}87})$

i.e. $F \leqslant \tfrac{1}{2}(1 + 0{\cdot}8 \times 10^{-2})$

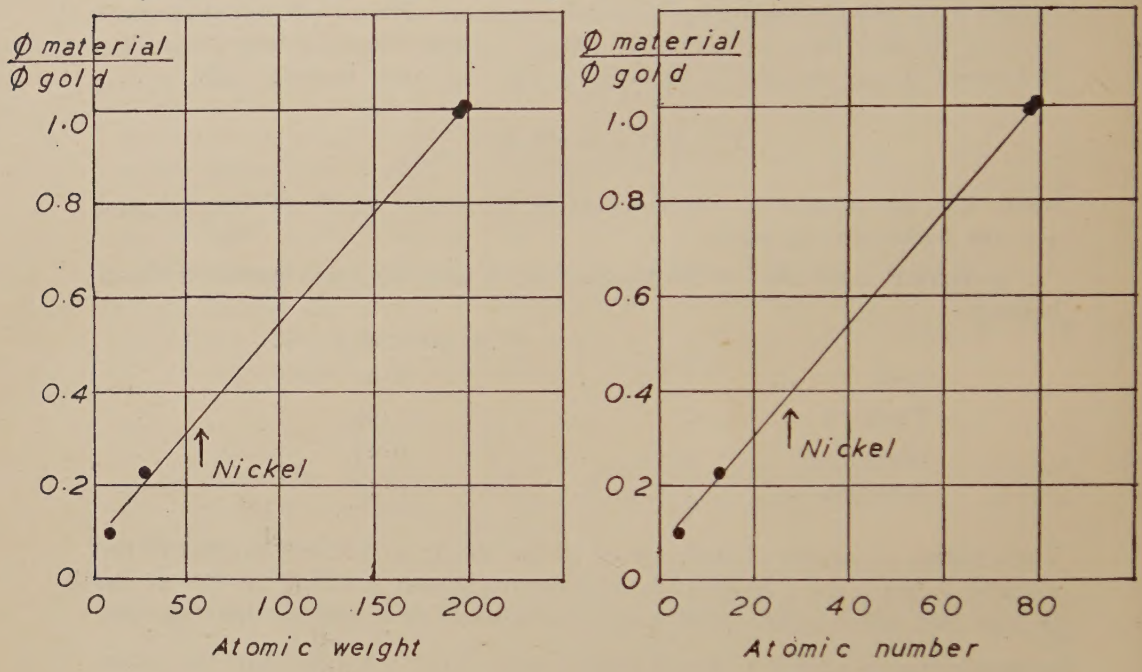
The true geometry must therefore be less than 50·4 per cent. Also, since the alpha particles emitted from the RaF source enter not air, but photographic emulsion, a number not negligible compared with 0·8 per cent must be scattered back out of the emulsion again without having gone far enough in it to leave a recordable trace. The net backscattering will thus be even lower than 0·8 per cent. Furthermore,

a comparison mentioned by Rossi and Staub between experimental and theoretical results for a uranium source on platinum gave the values :—

$$0{\cdot}201\ \phi = 0{\cdot}013 \text{ (experimental)}$$
$$0{\cdot}201\ \phi = 0{\cdot}016 \text{ (theoretical)}$$

which implies that the theoretical formulae may be high by about 20 per cent. Taking these facts into consideration, we can be reasonably sure in assuming that

Fig. 1 Backscattering of alpha particles Fig. 2



the geometry for nuclear plates placed in contact with a RaF source on nickel lies between 50 and 50·3 per cent, and a value of 50·2 ± 0·1% will be used for purposes of calculation.

The plates actually used were Ilford Type C.2, thickness 50 μ. Before leaving this subject it might be asked why the absolute beta activity of a source might not be determined directly, using electron sensitive plates such as the Kodak NT4A. Apart from the fact that these plates are still hardly beyond the experimental stage, two factors make the method impracticable. First of all, the low ionising power of the betas, and the tortuous beady tracks produced, will inevitably mean slowness in counting the developed plate, and the certainty of missing an appreciable

fraction of the tracks. Secondly, since large numbers of electrons are present in cosmic rays, an impossibly high background count is unavoidable. With alpha particles the stray count is entirely negligible, most of what there is being Ra and Th stars from the plate backing, and is easily recognisable as such since the tracks are out of focus. Two or three stars per 1000 RaF alphas would probably be a gross overestimate.

It was thus decided that recording by nuclear plates held advantages little offset by the rather laborious method of counting by microscope, but it was felt that a check by another method would be desirable, and an ionisation chamber counter and amplifier was used for this purpose. The chamber and first stage were constructed especially for this series of experiments, and are described more fully in Section 2. The chamber was designed to take large sources held in a horizontal position, in a manner that allowed them to be changed rapidly and safely. The output of the amplifier was fed to a soft valve scale of 16, final recording being on a P.O. call register. Naturally, such an uncalibrated counter could only give ratios of activities, say for example, the ratio of the activity of a RaF source after 20 days to its activity originally, but even as such provided a useful check on the ratios given by the plate method. Calculations from absolute values of activities, as measured by the plates, showed that the geometry of the counter was 5·5 per cent. The counter was corrected for small day-to-day changes in sensitivity by making counts on a constant source—actually a piece of autunite mineral.

One very useful role played by the counter was in the estimation of the activity of newly prepared sources. A very short run was sufficient to decide whether a source was unsuitable for further experiment, through the activity being either impossibly high or low. Waste of time and material in making long plate exposures on useless sources was thus eliminated. A great deal of approximate data was collected from early experiments, and four Ra(E + F) sources were used in the final estimation of the counter geometry. The method of preparation of these will be described later.

A source was placed in contact with a nuclear plate for a period depending on its initial activity, which naturally varied somewhat from source to source. From the experience gained with earlier sources it was easy to predict the exposure time necessary to give about 15 tracks per microscope field—the most suitable number for counting. According as the alpha activity grew, the time could be progressively decreased in order to keep this number approximately constant, and a suitable allowance made in the calculations. The limits of exposure for all sources lay between three and eight hours. The exposures were repeated at two-day intervals for at least 20 days in all cases. Assuming a geometry of 50·2 per cent the absolute growth of the RaF in the sources could thus be followed. Since the diameter of the source was 4·50 cm., and the plates had dimensions 3 in. × 1 in. (7·62 cm. × 2·54 cm.), not all the source was used in any one exposure. Using a reference scratch on the source, the latter was turned through a right angle for successive exposures, in order to eliminate possible errors due to the Ra(E + F) deposit being tangentially asym-

metrical. No effect due to this cause was, in fact, ever noticed. The deposit was found, however, to decrease a little towards the centre of the disc. This could be explained by assuming that deposition of Ra(E + F) was aided by increased motion of the solution over the nickel, and as can be seen from the method of deposition (Section 2) this was greater at the edges than at the centre. The method of counting, as described below automatically integrates small variations such as this.

Processing of the plates followed the standard procedure recommended by Ilford. They were then examined with a microscope of magnification 430, and a field of view of diameter $2 \cdot 875 \pm 0 \cdot 02 \times 10^{-2}$ cm. The range of RaF alpha particles in the emulsion is 22 μ. In examining the plate with the microscope the exposed area was repeatedly traversed parallel to the longer side of the plate. Roughly 10 fields were counted on each traverse, and in no case was the total number of fields counted less than 100. In many cases a recount, again with more than 100 fields, was made, and for the important initial point on each graph at least two recounts were made. representing a total of over 300 fields in all.

Fig. 3

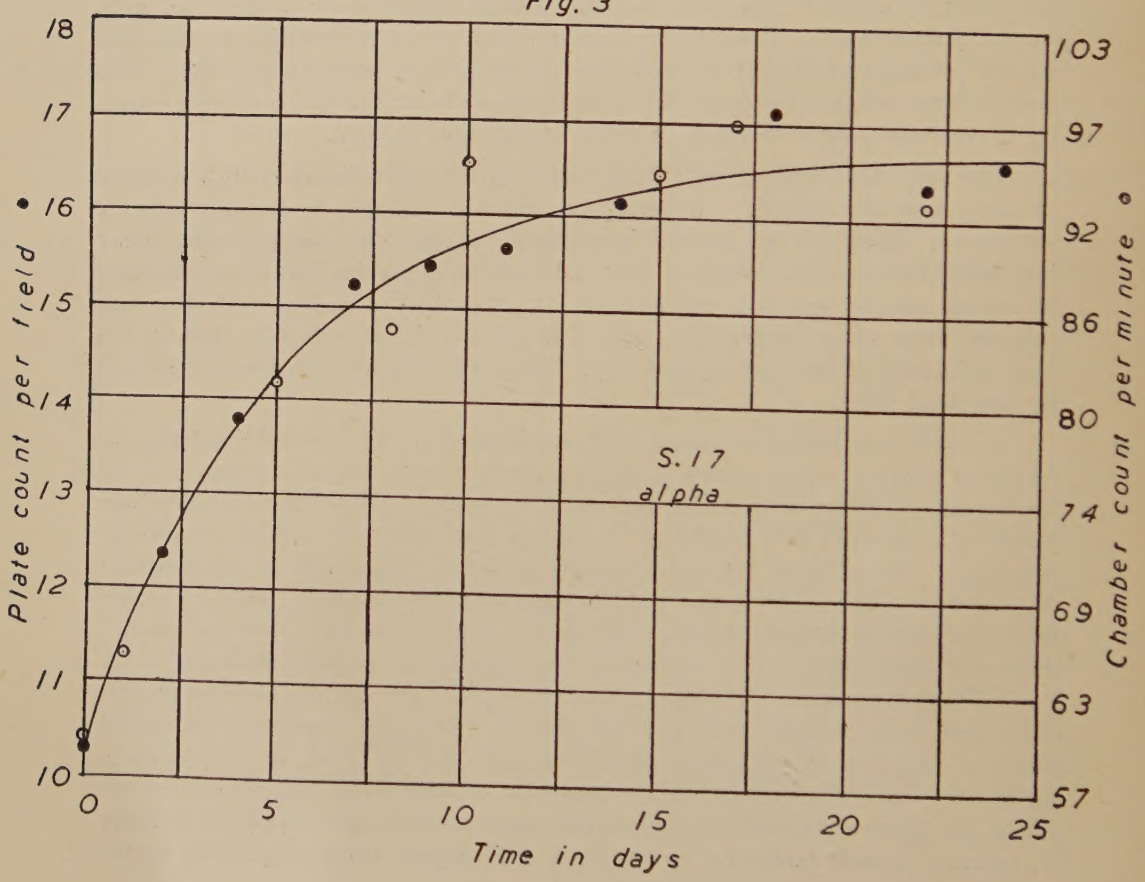


Fig. 4

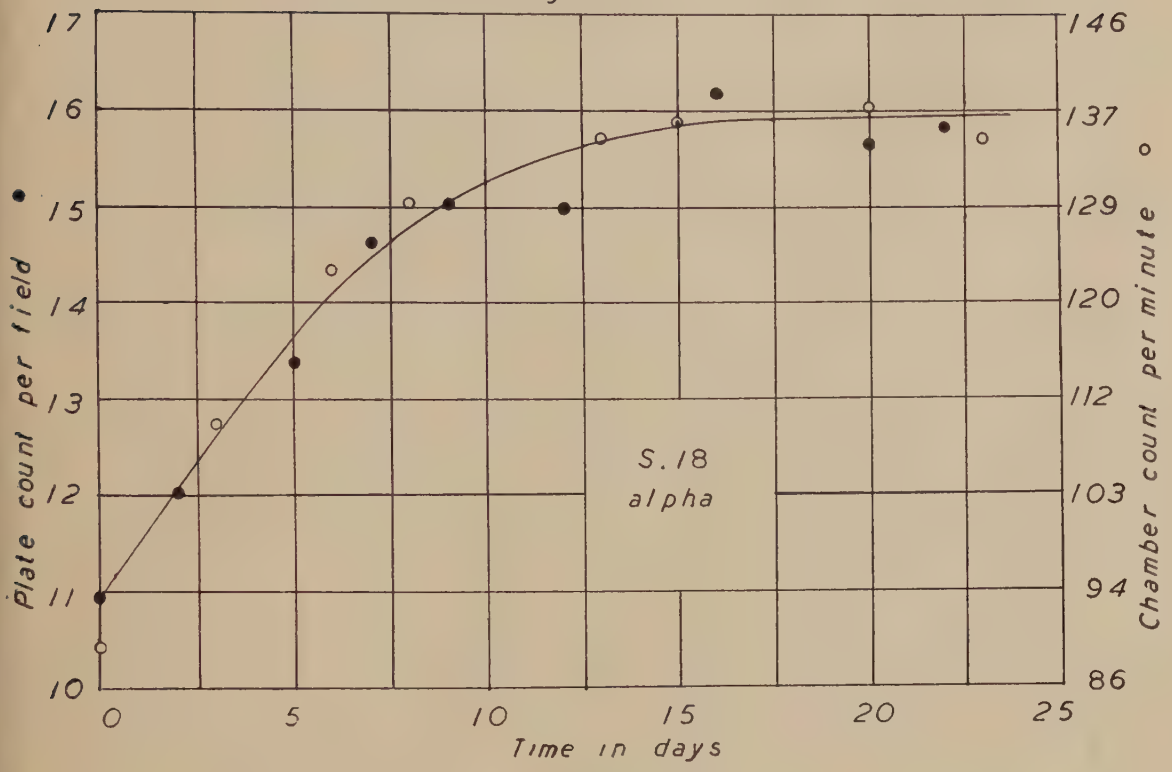

17
16
15
14
13
12
11
10
Plate count per field
146
137
129
120
112
103
94
86
Chamber count per minute
S. 18
alpha
0
5
10
15
20
25
Time in days

Fig. 5

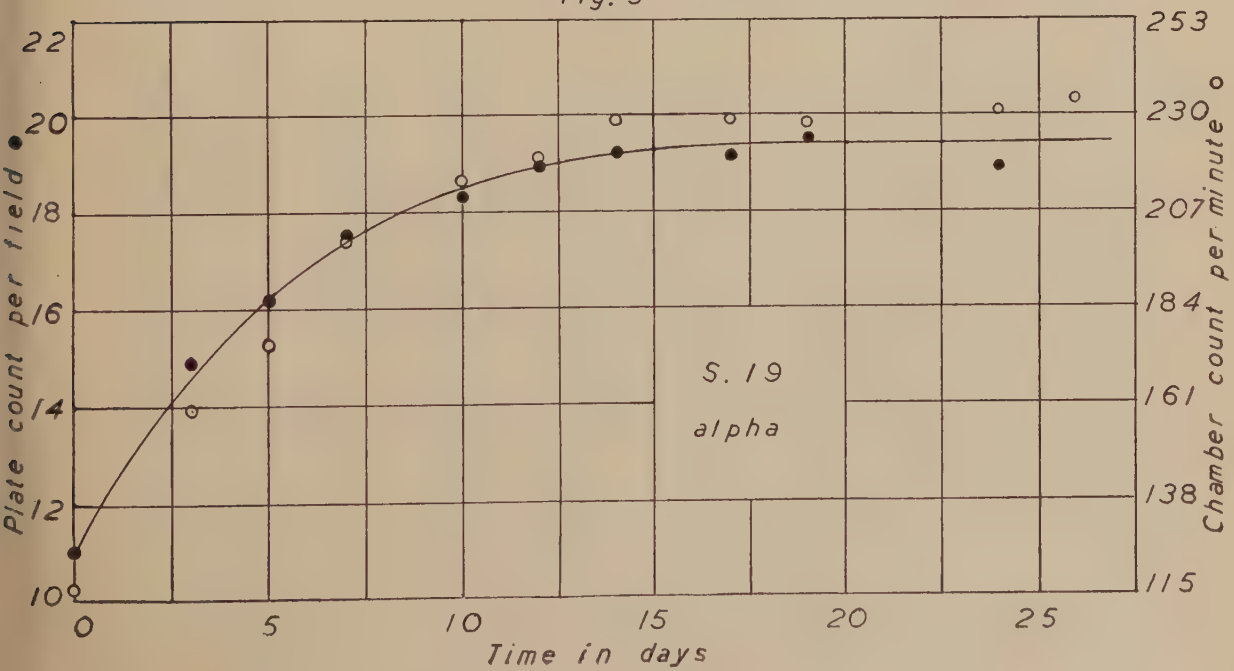
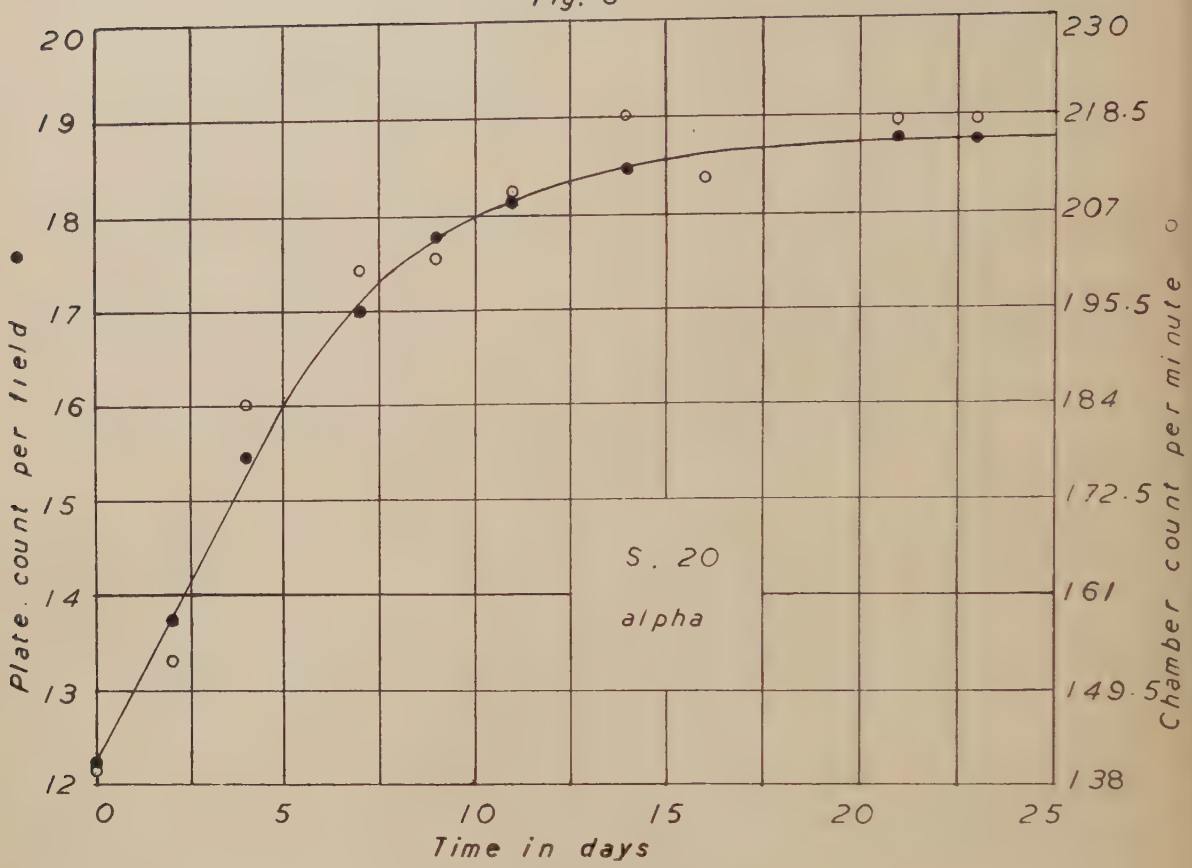

22
20
18
16
14
12
10
Plate count per field
253
230
207
184
161
138
115
Chamber count per minute
S. 19
alpha
0
5
10
15
20
25
Time in days

Fig. 6



The resultant graphs for the four sources S17, S18, S19, and S20 are shown in figs. 3 to 6. (Points marked with dots.) The improvement in the scatter of the points in the two later graphs, (S19 and S20) will be noticed. This was due to the plates used for S19 and S20 being markedly superior to those used for S17 and S18. The batch of plates used for S17 and S18, although developed with exactly the same technique, and in fact with the same developer, stop bath and fixer solutions as S19 and S20, were extremely grainy, almost as if they had been accidently subjected to a general strong dose of beta or gamma radiation. Consequently, the counting of the alpha tracks was in many cases a difficult task. With the next batch of plates, no graininess, with its consequent difficulties, was encountered. Since both batches received the same treatment, and were stored in the same place in the laboratory, it is unlikely that the graininess was due to any irradiation or other cause occurring after their receipt.

The circles on the graphs give the count as checked by the ionisation chamber, in counts/min. from the whole source. Incidentally, from the ratio of the two scales on the graphs, and the dimensions of the source and of the microscope field, the geometry of the ionisation chamber may be calculated. The geometries obtained from S17 and S18 by this method agreed very well with one another, and their average was 5·3 per cent. The values obtained from S19 and S20 also agreed well with one another at 5·7 per cent. The small difference in these figures (which of course had no bearing on any final results quoted) must be due to some change in characteristics of the counter not shown up in the autunite source count during the period of 45 days which separated the preparation of S17 and S18 and of S19 and S20.

It might be added that in any case of importance when the plate count and the count from the ionisation chamber disagreed significantly (such as in the initial point for S18), then, on principle, the former was accepted, since the plate provided a permanent record which could be rechecked as many times as desired.

From these four graphs the number of beta disintegrations/min. for each source at any time after its preparation can be deduced. In practice, the calculated count at 30 days (*i.e.*, 6 half lives of RaE) was chosen as most convenient for comparison with the measured beta count, as by then the activity was down to an amount that

Fig. 7

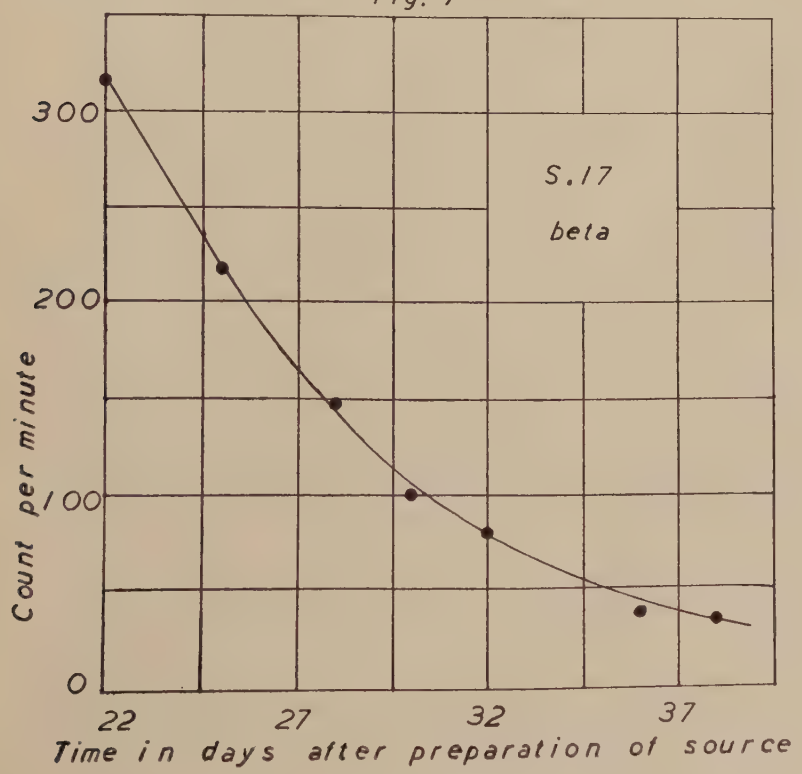


Fig. 8

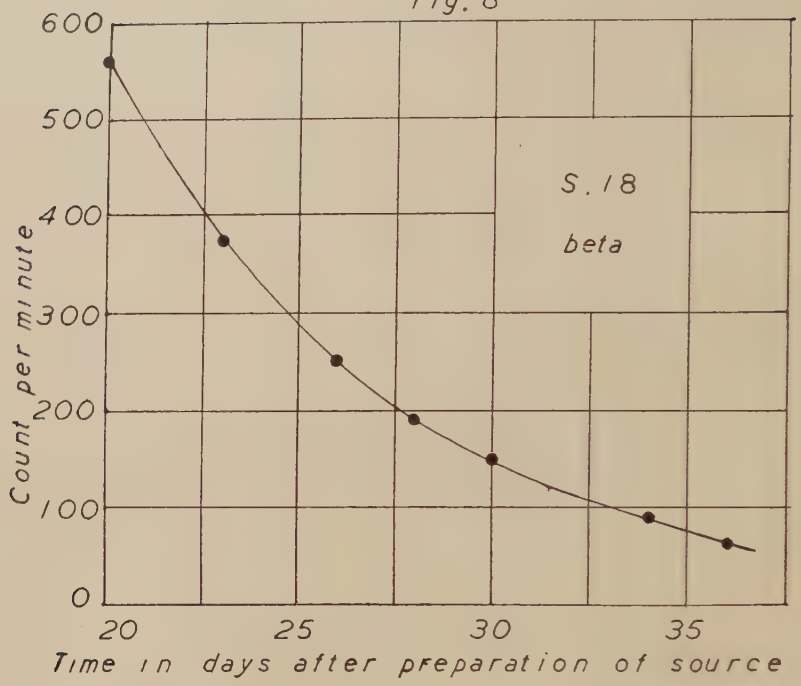
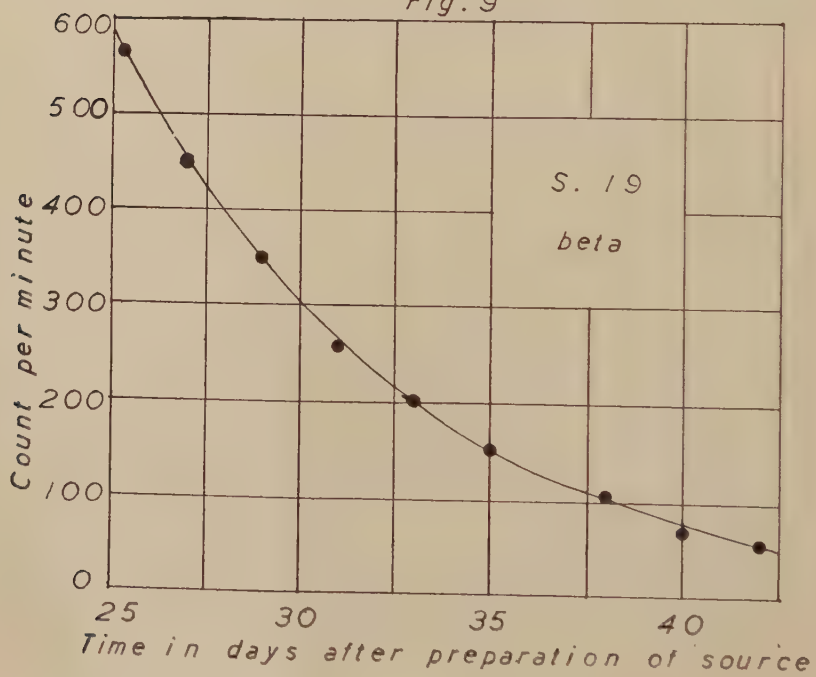
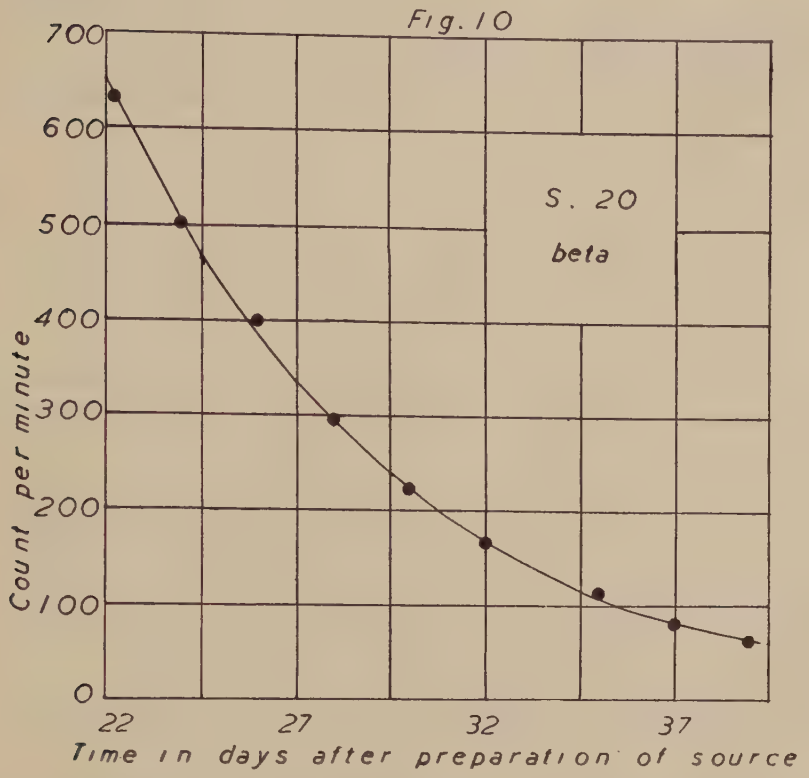

600
500
400
300
200
100
0
Count per minute
S. 18
beta
20
25
30
35
Time in days after preparation of source

Fig. 9


600
500
400
300
200
100
0
Count per minute
S. 19
beta
25
30
35
40
Time in days after preparation of source



the recording apparatus could conveniently handle. Theoretically, just one measure of the beta activity at this time is all that is needed, but in order to check, among other things, the performance of the scaler, and the purity of the RaE, the decay curve of the latter was followed for at least 15 days (3 half lives), starting from 20 to 25 days after the source preparation, depending on the source. The corresponding graph for the four sources are shown in figs 7—10. If the RaE were accompanied by some RaD (as was at one stage feared), then, although the extremely soft betas from RaD would make no direct contribution to the count, yet the presence of the RaD, as parent of RaE, would make the latter appear to have a half life greater than its normal 5 days. The subsequent calculations would then, of course, be valueless. Contrariwise, if no RaD were present then the RaE activity would be observed to drop exactly by half every 5 days, provided the scaler was working correctly. That is, the value of the activity at the beginning of the actual beta counts on the source should be twice that 5 days later, 4 times that 10 days later and 8 times that 15 days later. Due to the finite resolving time of the scaler, the initial count will be down somewhat with respect to later ones. The maximum discrepancies observed were 5 per cent, 7 per cent, 3 per cent, and 4 per cent for S17, S18, S19, and S20, respectively. There was little or no discrepancy between the count for 5 days and twice that for 10 days, etc. That these discrepancies were indeed due to the

finite resolving time of the scaler, and not to the presence of RaD, was shown roughly by the following subsidiary experiment.

Two powdered uraninite sources gave counts of 350·6/min. and 338·8/min., respectively. Together, (and each in its previous position) they gave a count of 658·8/min. That is the per cent loss is :—

$$\frac{689{\cdot}4 - 658{\cdot}8}{689{\cdot}4} \times 100 = \frac{30{\cdot}6}{689{\cdot}4} \times 100 \doteqdot 4{\cdot}5\%$$

So in dropping from about 690 counts/min. to half that value, an error of 4½ per cent is introduced. This is about the same order of error as in the main experiment, where the count dropped from an original activity of from 300 to 600 counts/min., depending on the source, to a final value of less than 100 counts/min., in all cases.

This error of 4½ per cent does not speak very well for the resolving time of the scale of 16. Although the deionising time of the thyratrons in the first stage may have increased with age, and helped to cause the loss, it is felt that the large RC grid constants of the first scale of 2 was mainly responsible. These could have been decreased considerably for the fast beta pulses, with consequent improvement in resolving time, but as the same scaler was used for alpha recording this was not possible, as it led to grave attenuation of the much slower alpha pulses. A suitable discriminator circuit on the input would probably have solved the difficulty. Although the question of losses has been treated here at length for the sake of interest, it does not in any way affect the final results, as the actual count used for comparison with the true deduced activity was taken at 30 days after the source preparation, *i.e.*, at a time when the beta count was low enough to make resolving time losses negligible.

From these four graphs of beta decay, and the four preceding ones for the alpha activity, the counter geometry may be determined as follows. If n_{E0} and n_{F0} are the numbers of atoms of RaE and RaF present originally in a source, then n_F, the number of atoms of RaF present at time t, is given by the equation :—

$$n_F = n_{F0}e^{-\lambda_F t} + \frac{\lambda_E n_{E0}}{\lambda_F - \lambda_E}\left(e^{-\lambda_E t} - e^{-\lambda_F t}\right)$$

where λ_E and λ_F are the disintegration constants for RaE and RaF. From this it can be easily deduced that :—

$\lambda_E n_{E(30)}$ (the number of disintegrations/min., of RaE after 30 days)

$$= \frac{343{\cdot}4}{h}\left(\frac{c_F - c_{F0}\, e^{-0{\cdot}6931t/\tau_F}}{e^{-0{\cdot}6931t/\tau_F} - e^{-0{\cdot}6931t/\tau_E}}\right)$$

$= 343{\cdot}4\ (\psi/h)$ say.

Here c_{FO} and c_F are the plate counts/field originally and at time t, h is the number of hours exposure and the half lives τ_E and τ_F have been used instead of the corresponding disintegration constants. The factor 343·4 takes account of, among other things, the relative areas of the microscope field and source, and the counting efficiency of the plates, 50·2 per cent.

The values of c_F are read from the alpha growth graph for a particular source, at times 0, (which of course gives c_{FO}), 5, $7\frac{1}{2}$, 10, $12\frac{1}{2}$, 15, $17\frac{1}{2}$, and 20 days. The corresponding values of ψ are then calculated, (their constancy being a verification of the general correctness of the method), and their mean used in determining $\lambda_E n_{E(30)}$ from the final equation above. These calculations are displayed in Table 1, below.

Values of ψ deduced from c_F at $t = 2\frac{1}{2}$ were found to be unreliable because of the small increase in the source activity after such a short time, and were ignored. Growth curves extending beyond 20 days were available for some sources, but since here the graphs become almost parallel to the time axis, and the exact values of c_F difficult to determine, values of ψ deduced from them were also rejected.

Before giving the actual table of ψ for the four sources, one further result is worth quoting. It can easily be shown that :—

$$\frac{n_{FO}}{n_{EO}} = \frac{\tau_F}{\tau_F - \tau_E}\left(\frac{c_{FO}}{\psi}\right) = \frac{28}{27}\left(\frac{C_{FO}}{\psi}\right)$$

and it is from this formula that the figures previously given concerning the relative amounts of RaF and RaE present initially were deduced.

Table 1.

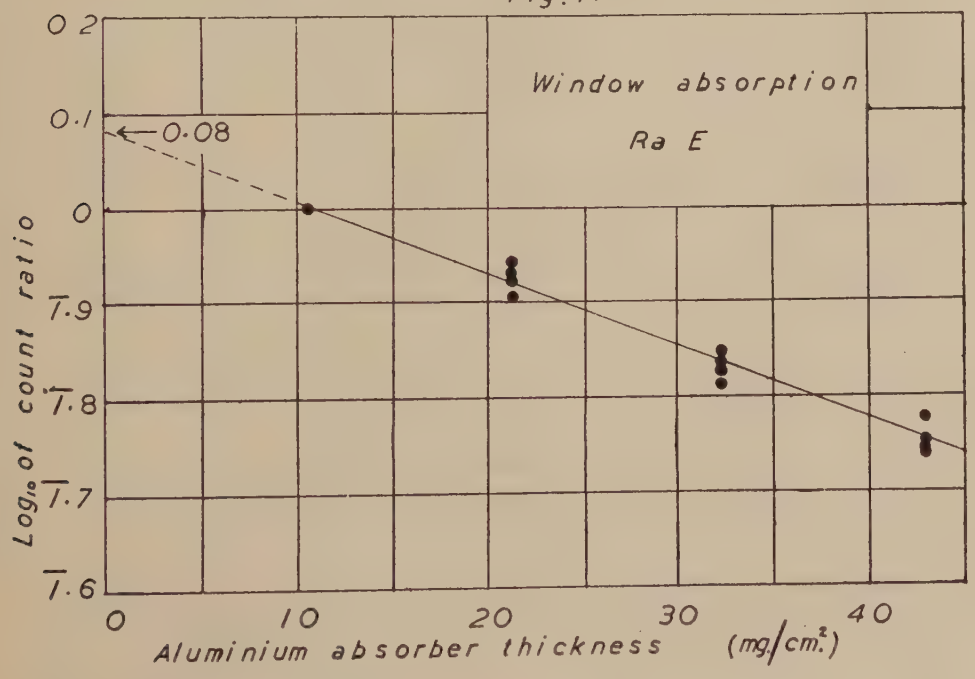
	S17		S18		S19		S20	
t, (days)	c_F	ψ	c_F	ψ	c_F	ψ	c_F	ψ
0	10·31		10·96		11·03		12·23	
5	14·3	8·917	13·70	6·330	16·3	11·65	16·1	8·768
$7\frac{1}{2}$	15·15	8·553	14·65	6·705	17·6	11·42	17·3	9·035
10	15·7	8·395	15·25	6·869	18·5	11·40	17·95	9·007
$12\frac{1}{2}$	16·05	8·337	15·65	7·013	19·0	11·32	18·3	8·925
15	16·3	8·377	15·85	7·069	19·3	11·29	18·55	8·962
$17\frac{1}{2}$	16·5	8·506	15·9	7·049	19·35	11·15	18·65	8·980
20	16·6	8·616	15·95	7·145	19·4	11·16	18·7	9·038
ψ mean		8·529		6·883		11·341		8·959
h	$7\frac{1}{2}$		5		4		4	
$\lambda_E n_{E(30)}$	390·4		472·5		973·4		769·0	
expt. beta count at t = 30	107·5		150·3		299·0		221·7	
geometry %	27·54		31·81		30·72		28·83	
$\frac{28}{27} c_{FO} = \frac{n_{FO}}{n_{EO}}$	1·253		1·652		1·009		1·416	

Grand average of geometry, (weighting results from S19 and S20 twice as heavily as those from S17 and S18) = 29·7(4)%

The reason the geometries as deduced from S19 and S20 are weighted twice as heavily as those deduced from S17 and S18 in finding the mean, is on account of the better plates used with the two former sources, as discussed previously. As a matter of fact, the four separate geometries are so symmetrically distributed that the straight forward mean would differ only slightly from the weighted mean. As can be seen the actual result obtained is 29·7(4) per cent for the whole 4π solid angle.

The first correction to be applied to this figure is for window absorption of the RaE beta particles. This was found empirically as follows. Counts were taken on a RaE source as usual, that is really through an absorber of thickness equal to the window thickness and air space between source and window, *i.e.*, 9·6 mg./cm.^{2} + 1·0 mg./cm.^{2} = 10·6 mg./cm.^{2} total. Putting in an additional mica absorber of thickness 9·5 mg./cm.^{2} on the shelf provided (see fig. 18), the count through a total of 20·1 mg./cm.^{2} was found. Similarly, the counts through total thicknesses of 32·0 and 43·9 mg./cm.^{2} were obtained. Mica absorbers were used to simulate exactly the beta absorption in the window. Anomalous results obtained with these were traced to radioactivity of appreciable amount in the mica itself. Three absorbers of total thickness 33·3 mg./cm.^{2} were found to give an additional count of 24·5/min. on a background of 42/min. (From this it appears that a slightly lower background count could have been achieved with a metal, rather than a mica window in the counter.) Aluminium absorbers were then substituted for the mica ones, and no anomalous effects noticed. Since the absorption of beta rays varies little from one

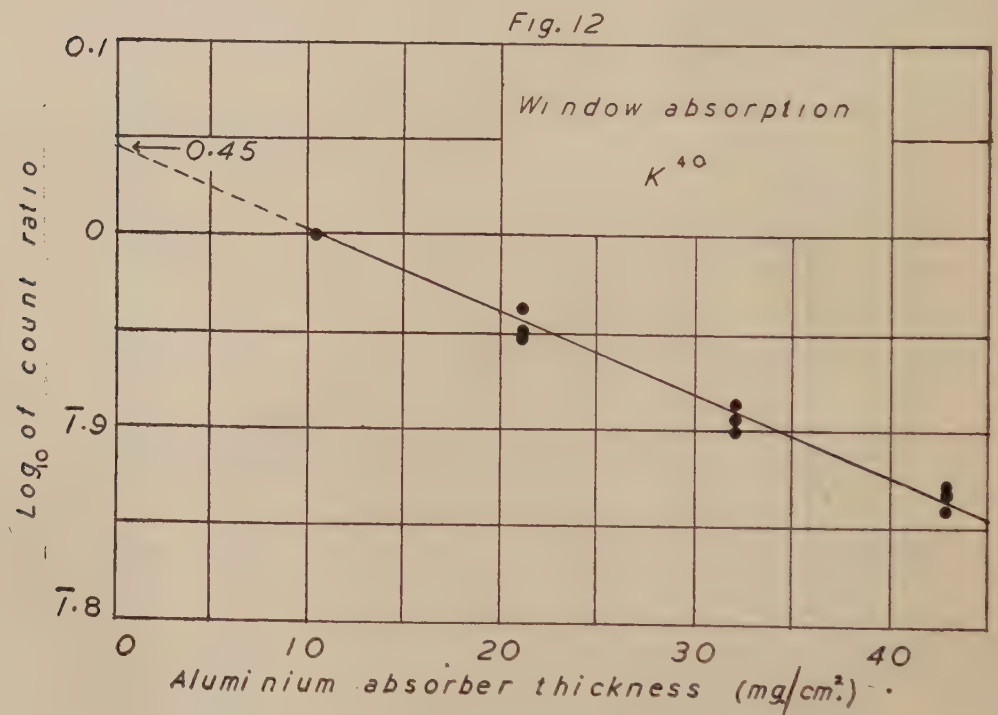
Fig. 11



material to another if the thickness is expressed in mg./cm.^{2}, it is unimportant if the window is mica and the absorbers aluminium. The experiment was repeated a number of times and the collected results are shown in graphical form in fig 11. The count through the window + air space has been taken as unity in all cases, and the counts through various absorbers expressed as fractions of this. Since the absorption of beta rays in a material is at first approximately exponential, the logarithm (to the base 10) of this fraction has been plotted against thickness as shown. The correction factor to be applied is seen to be $10^{0\cdot08}$, *i.e.*, 1·202, and the corrected geometry becomes 35·7(6) per cent.

Burtt (5) stresses the point that it is in these window corrections that the largest errors in the determination of the geometry are likely to arise, especially when dealing with beta emitters of energy less than 1 MEV, and he recommends that every point on the graph be representative of a very large number of actual disintegrations, (50,000—100,000). Each group of points in fig. 11 represents between 18,000 and 31,000 betas counted, the points corresponding to less absorber present naturally having the larger number of counts. The estimated error is still, however, the largest of all the individual errors in the whole investigation, 2·33 per cent (see Section 3.)

Fig. 12, the analogous graph for KCl, might also be discussed at this stage, In this, each group of points represents between 14,000 and 19,000 disintegrations.



and the estimated error is lower at 1·17 per cent, there being less spread in the points obtained. The window absorption factor is here $10^{0.045} = 1.109$.

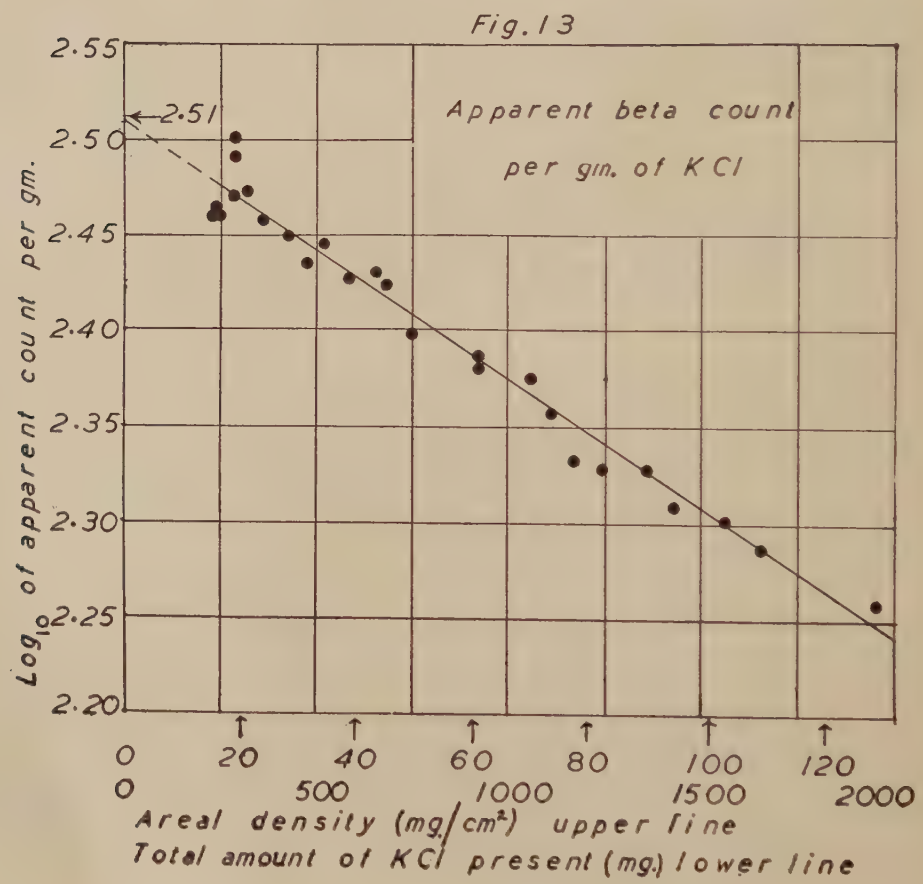
To return to the corrected counter geometry as given above, the figure of 35·7(6) per cent may at first sight appear rather large. This is because no account has as yet been taken of beta backscattering. In contrast to alpha particles, a large fraction of beta particles leaving the deposit of RaE in the direction of the nickel are, on account of their smaller mass, easily deflected by electronic or nuclear collisions back in the direction of the counter again. This backscattering, naturally, depends on the backing material of the source, and for a given material it increases as the thickness of the backing is increased, until this thickness is about 1/5 of the range of the beta particles in the material (7, 8). Here a further increase in thickness yields no corresponding increase in backscattering, and saturation backscattering is said to exist. For RaE on nickel, Burtt reports a saturation backscattering factor of 1·50, *i.e.*, the beta count is increased in the ratio 3/2 from that with an infinitely thin backing. These backscattering factors are not always easy to obtain, and show some anomalies with various backing materials, so it is fortunate that in most investigations their determination can be circumvented. This is because the saturation backscattering with a particular backing is independent of the beta emitter, provided the maximum energy of the latter is greater than 0·6 MEV. (5, 8, 9.) Hence, if the RaE ($E_{max.} = 1.17$ MEV) and KCl (K^{40}, $E_{max.} \sim 1.5$ MEV, discussed later) are both used with sufficiently thick nickel backing, the backscattering correction factor can be ignored. The maximum energy of K^{40} (~ 1.5 MEV) corresponds to a thickness of 700 mg./cm.^{2} of aluminium, and for saturation backscattering the nickel backing thickness must be greater than 1/5 of this—*i.e.*, 140 mg./cm.^{2} The 1/100 in. nickel used is equivalent to 225 mg./cm.^{2} and thus an ample margin of safety for the K^{40} beta particles is ensured. RaE, with a lower maximum energy, is even better provided for.

We have shown above that the actual value of the backscattering factor does not enter into the final determination of the specific beta activity of potassium. It is, however, of interest to apply this backscattering correction, that is to find what the geometry would be if the RaE were mounted on a very thin backing producing negligible scattering. We can then compare this, firstly, with the results of some other workers, and secondly, with a theoretical calculation of the geometry, to follow later.

The geometry with a thin backing, would, of course, be 35·7 (6)/1·50 = 23·8 (4) per cent. Burtt, (5) using a counter with a 2·2 cm. diameter cathode, and a RaE source of diameter 1·13 cm. held at a distance of 16·6 mm. from the counter window, found a value of 7·38 per cent for his geometry. Wu, Meaker, and Glassford (10), using a counter of diameter 2·86 cm. and a uranium source of diameter 1·8 cm. at a distance of 3 mm., from the window, state that 25 to 30 per cent of all betas leaving the source are counted. For comparison, the counter used in this experiment had a cathode of diameter 5·05 cm., and the sources of diameters 4·50 cm., were

placed 6·6 mm., from the window. The geometry of 23·8 per cent is of the same order as obtained in the two references above.

Once the geometry is known, the next step is the determination of the count per gm., of KCl. Shallow nickel pans of the same diameter as the RaE sources, were used to hold fine crystalline KCl, chemically pure. Self absorption of the K^{40} beta particles takes place, of course, in the KCl and consequently the count/gm., of KCl must be extrapolated to zero thickness. To that end KCl sources of various weights (and therefore various thicknesses) were made up, and their apparent count/gm., determined. This increases as the amount of KCl present decreases. By plotting a graph of apparent count/gm., against thickness of KCl and extrapolating this to zero, the true value of the count/gm., of KCl may be obtained. Actually, since it is known that this curve is approximately exponential if the thickness is not too great, the logarithm (to the base 10) of the apparent count was plotted against the thickness, and a straight line should be obtained. Fig. 13 shows that over the range considered, *i.e.*, 15 to 130 mg./cm.^{2}, this was indeed the case, within the limits of



experimental error. Naturally, the scatter of the points at the lower thicknesses is large because of the small amount of KCl present, and the resultant small total count.

The extrapolated count/gm. of KCl is seen to be $10^{2\cdot51} = 323\cdot6$ betas/min./gm. KCl. Applying the correction factor for window absorption of K^{40} beta particles, previously discussed, results in a count/gm., of KCl of $323\cdot6 \times 1\cdot109$, that is $358\cdot9$ betas/min./gm., KCl. Combining this with the previous value for the G.M. counter geometry, 35·76 per cent, and allowing for the potassium content of KCl, the count/sec./gm., of ordinary potassium becomes :—

$$358\cdot9 \times \frac{100}{35\cdot76} \times \frac{74\cdot553}{39\cdot096} \times \frac{1}{60} = 31\cdot8(9)$$

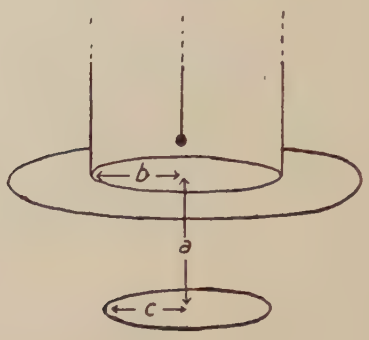
i.e., 31·9 betas/sec./gm., of ordinary potassium.

If we assume Nier's latest value (11) for the abundance of K^{40} in $K - 1\cdot19 \times 10^{-2}$%, a value of $5\cdot5 \times 10^{-10}$ yrs.$^{-1}$ is obtained for the beta disintegration constant of K40, with a corresponding half life of $1\cdot25 \times 10^{9}$ yrs.

It is natural to enquire whether the presence of the gamma radiation from potassium may not have led to an apparent value of the beta activity much higher than the true value. The following considerations, however, rule out this possibility. To begin with, it is extremely difficult, even with quite a thick-walled G.M. counter, to raise its efficiency to 1 per cent for gamma rays (12) ; so even if the gamma activity of potassium were comparable with its beta activity, (while, in fact, nearly all workers agree that it is about 10 per cent of it) then with the thin window counter tube used the gamma contribution would be entirely negligible. If more direct evidence is desired it can be found in the absorption curve of K^{40} beta rays in aluminium to be discussed later. (Fig. 16). If significant gamma effects were present, then this curve should level out at moderate absorber thicknesses. As, on the contrary, it can be seen that the graph falls steadily to zero, at least up to the maximum thickness of 300 mg./cm.^{2} utilised, we can conclude that the figure of 31·9 does indeed represent the true beta count/sec./gm. of ordinary potassium.

Two further questions remain to be discussed. Firstly, a calculation of the geometry was made for comparison with the experimental determination. The problem is to determine the solid angle subtended by an upper circle of radius ' b ' (the counter window, see fig. 14) at a representative point P on a lower disc of radius ' c,' (the source) and then to integrate this result over the whole of the lower disc. The distance between source and window is assumed to be known, ' a ', let us say. According to Blachman (13), the result of this calculation of the geometry may be expressed as a series in γ $(= c^2/a^2)$ with coefficients which are functions of β $(= b^2/a^2)$, and the series converges for all β if γ is not too large. For the geometry used ' b ' = 2·525 cm., ' c ' = 2·25 cm., and ' a ' = 0·66 cm. This gives a value of G = 32·2 per cent which is very much higher than the value of 23·8 per cent obtained experimentally and corrected for backscattering. The discrepancy lies in the fact that

Fig. 14

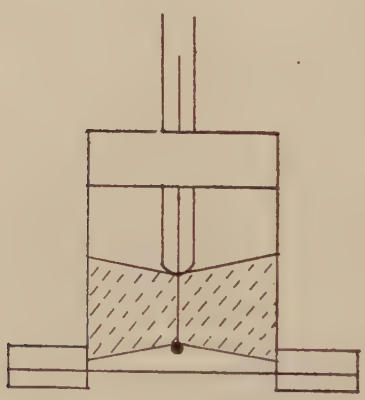


Counter geometry

the active volume of the counter, that is, the region into which a particle must pass to be counted, does not commence at the window but some distance back from it. If we assume, then, that the active volume begins just inside the pyrex bead on the anode wire, ' a ' becomes 1·41 cm., with ' b ' and ' c ' as before, and the calculated geometry is now 20·7 per cent.

It is seen, then, that the experimental geometry lies between the two calculated geometries, but much nearer to the latter, and the state of affairs is probably as indicated in fig. 15. Here the active volume is shown shaded, and near the wall, it extends, on account of the large radius of the counter, a little forward of the pyrex

Fig. 15



Active volume of counter

bead. The agreement between theory and experiment is considered reasonably satisfactory, considering how rapidly the calculated geometry varies with the distance 'a'.

The problem of the calculation of counter geometry has also been treated by Cook, Duncan, and Hewitt (54). Their results are presented in graphical form, and when applied to the present problem lead to geometries of 31·5 per cent and 20·5 per cent for the two cases discussed. These figures are in close agreement with the values of 32·2 per cent and 20·7 per cent quoted previously.

The second and final matter to be discussed is the question of the radioactive purity of the KCl used. If even very small amounts of some natural beta emitter of high activity were present, they might make an appreciable difference to the apparent emission of the low activity potassium. To prove the absence of any such radioactive impurities two sources of KBr were prepared, the KBr being of different origin (*i.e.*, supplies by a different manufacturer) from the KCl. The count/gm. KBr for each source, with the usual geometry, was determined, and the corresponding count/gm. KCl at the same source thickness obtained from fig. 13. If the beta activity is due only to potassium, the ratio of these two counts should be in the ratio of the potassium content of KBr to the potassium content of KCl, *i.e.*, 0·627. The figures obtained (see table 2 below) were 0·642 and 0·614, the mean of which, 0·628, agrees almost completely, but a trifle fortuitously with the theoretical value of 0·627 quoted above. We can thus feel confident that no radioactive contaminant is present in the KCl used in the original experiment.

Table 2.

KBr	Weight (gms.)	Thickness (mg./cm.)	Count/min.	Count/gm./min.	log (count/gm.^{10} KCl at same thickness), from fig. 13	count/gm. KCl at same thickness	KBr/KCl count ratio
Sample 1	1·515	99·6	196·2	129·5	2·305	201·8	0·642
Sample 2	1·067	70·2	152·3	142·8	2·365	231·7	0·614
						Mean.....	0·628

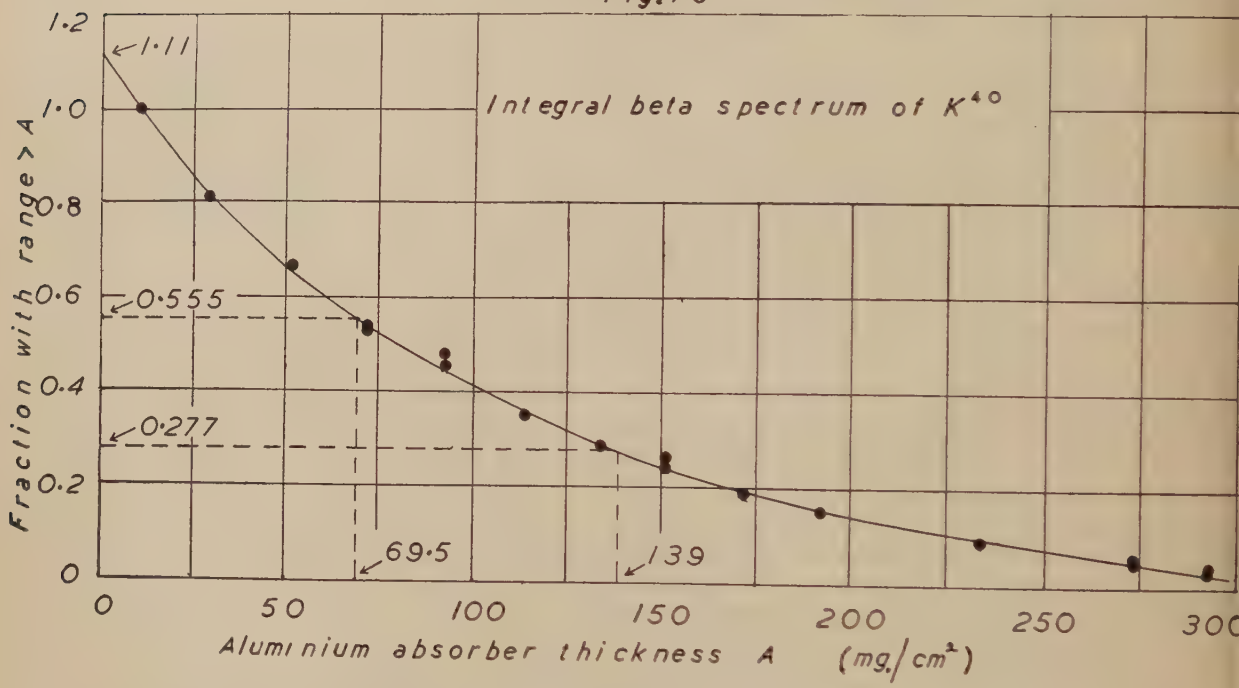
Ratio of potassium in KBr and KCl,

$$= \frac{0{\cdot}3285}{0{\cdot}5244} = 0{\cdot}627$$

The Absorption of K^{40} Beta Rays.

Studies of the absorption of the K^{40} beta rays in aluminium were made with a view to eventual energy determinations. Screens of this material were placed in position between source and window on the ledge provided, (see fig. 18) just as in the window absorption experiments described previously, only here, however, the measurements were carried out to much greater absorber thicknesses. Since these absorbers will rapidly reduce the count from a KCl source to a small fraction of its original value, it was necessary to commence with as large a count as possible. For this reason a much thicker source was needed than in any of the previous experiments. A deep, brass, source holder made for this purpose had a diameter of 3·60 cm., and contained 6·028 gms. of KCl. This corresponds to a thickness of 592·(4) mg./cm.^{2} As can be seen from the first curve obtained (fig. 16), only an extremely small fraction

Fig. 16

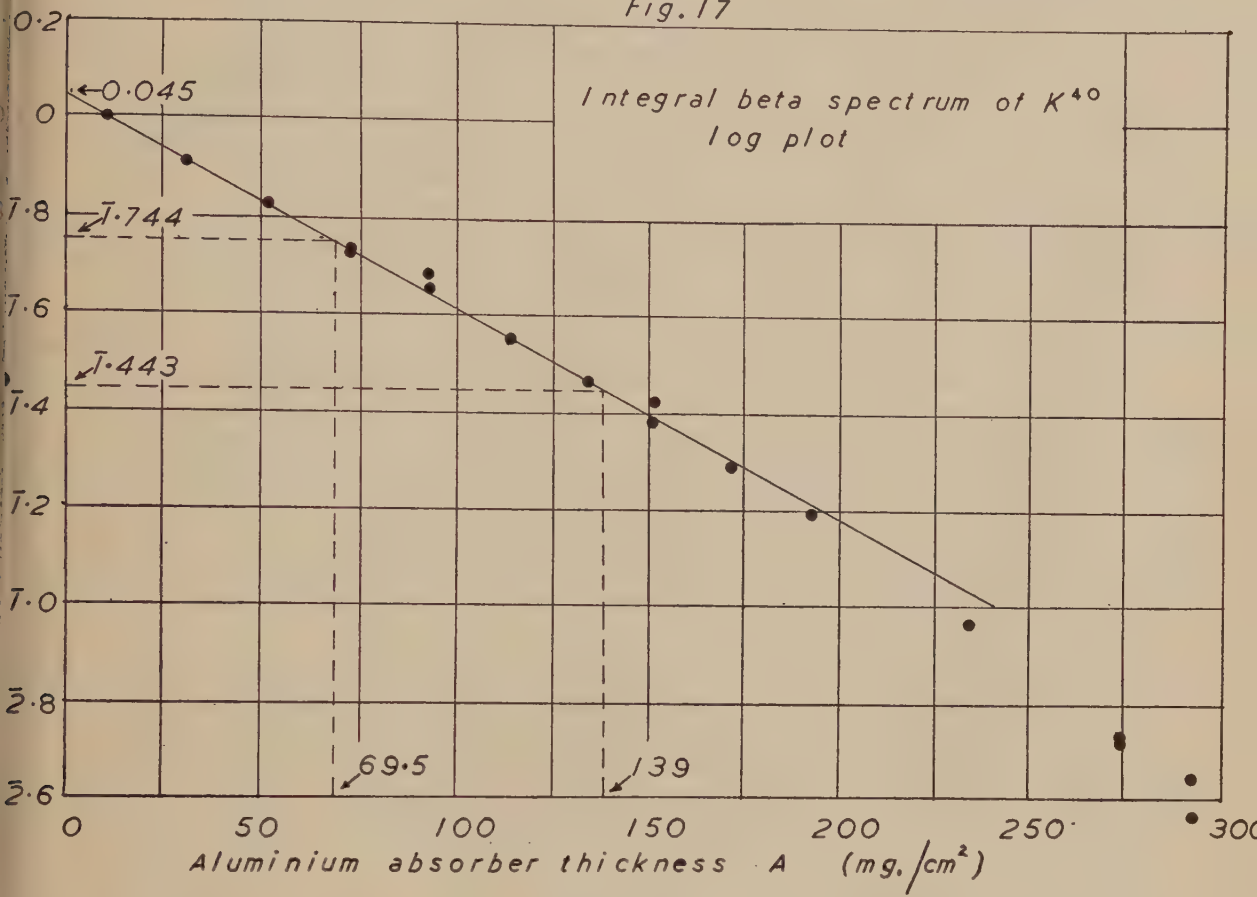


of beta particles from the lower layers of a source of this thickness will arrive at the surface ; we have, therefore, to all intents and purposes, an ' infinitely thick ' source.

All counts obtained were expressed as fractions of the count with only the counter window and air space as absorber. The plot of this fraction against absorber thickness is shown in fig. 16. (It is to be noted that the window correction deduced from this curve agrees well with the more accurate one found previously using three thinner

absorbers.) Since the absorption is known to be approximately exponential, at least for fairly small thicknesses, the logarithm to the base 10 of the previous fraction was plotted against absorber thickness in fig 17. It is seen that an exponential law is

Fig. 17



well obeyed to a thickness of about 200 mg./cm.,² the actual graph after this falling below the exponential plot. This is to be expected, as an exponential law would predict some betas even at very large thicknesses, whereas we know that actually no betas are emitted with energies greater than a certain limiting value. It is not practicable to proceed farther than 300 mg./cm.,² as even here the count is only about 13/min. on a background of 45/min. The ' half thickness ' for the K^{40} beta rays, that is, the amount of absorber required to reduce their intensity by half, can be read off from either fig. 16 or fig. 17, but more easily from the latter, and is seen to be 69·5 mg./cm.² The ' quarter thickness ', at 139 mg./cm.,² agrees with this exactly, to within the limits to which the graph may be read. (It must be borne in mind in reading off the half thickness from, say, fig. 16, the direct plot, that we

must look for it not at a point corresponding to an ordinate of 0·5, but at one of 0·555. This is because the relative intensity corresponding to zero absorber is 1·11, the value of 1·0 being reserved for the relative intensity through 10·6 mg./cm.^{2} of window and air space.)

While the ' half thickness ' is of importance for practical measurements, the maximum energy limit is of much greater theoretical value. With a source of sufficiently high specific activity, a direct determination of the latter is possible, simply by following the absorption curve to the limit. Even with somewhat weaker sources, where it is not possible to follow the absorption curves to near the limit, a method has been devised by Feather (14), in which, by comparing the absorption curves of RaE and the unknown beta rays to the greatest absorber thickness convenient, the upper energy limit of the latter may be predicted quite closely from the known maximum energy of the RaE rays. Feather has further treated the same problem for fairly thick sources, but only for cases where the source thickness is less than R/4, (R being the maximum range of the beta rays in the material of the source).

Clearly, then, certain numerical factors which he deduces for use in such circumstances are not applicable, where, as in the case of K^{40}, the specific activity is so remarkably low that an ' infinitely thick ' source must be used. These difficulties would have been eased considerably if, like Hirzel and Waffler, (15) a cylindrical thin-walled counter had been used, for then the source area could have been increased, its thickness diminished accordingly, and the formulae of Feather utilised. The same result could have been obtained, while retaining an end window counter, by using potassium electromagnetically enriched in the 40 isotope, as was done by Borst and Floyd (16, 17).

Even with the available arrangement, however, an estimate of the maximum beta energy can be obtained if an empirical relation between this quantity and the half thickness is available. A formula due to Mlle. Perey supplies precisely this. She found (18) that, for 16 different artificial radioisotopes with maximum energies ranging from 0·6 to 5 MEV, the law :—

$$E_{max.}\ (\text{MEV}) = \frac{A_{\frac{1}{2}}\ (\text{gms./cm.}^2) + 0{\cdot}008}{0{\cdot}047}$$

was well obeyed for the energy range in question. Here $A_{\frac{1}{2}}$ is the half thickness in copper, but since the absorption of beta rays varies little with absorber material provided the thickness is expressed in mg./cm.^{2}, the change from copper to aluminium will have little significance. Substituting, then, the experimentally obtained value for the half thickness of the K^{40} beta rays, 0·0695 gms./cm.^{2} of aluminium, in the above formula, gives their maximum energy as 1·65 MEV. It is difficult to decide just what confidence is to be placed in this estimate. Certainly the formula quoted above fits Mlle. Perey's experimental data very closely. Further, it is fortunate that she used sources of thickness 0·5 gms./cm.^{2},—very little different from that of 0·592 gms./cm.^{2} used in the present work, especially since she states that no corrections are necessary for sources thicker than those used by her, ' infinitely thick '

conditions being already supposed to exist. Nevertheless, since her work was done with a thin-walled counter having a different geometry, (with consequent differences in scattering) from that used in these experiments, the result of 1·65 MEV deduced above is probably to be trusted only to 10 or 20 per cent.

Before leaving this question, it is worth mentioning a figure obtained before the present author was aware of Mlle. Perey's work on the subject. From a consideration of data given by Mme. Joliot Curie (19) on the maximum energy and half thickness in aluminium for a number of natural beta emitters, the following approximate formula was decided upon :—

$$E_{max.}\ (MEV) = A_{\frac{1}{2}}(gms./cm.^2) \times 24{\cdot}6$$

that is :— $$E_{max.}\ (MEV) = A_{\frac{1}{2}}(gms./cm.^2)/0{\cdot}0406$$

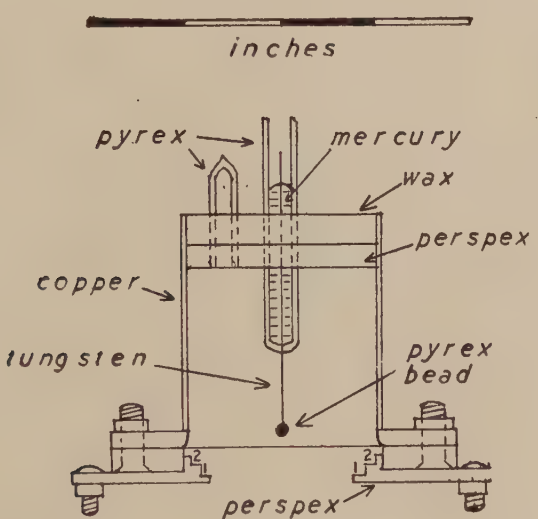
This yields a value of $E_{max.} = 1{\cdot}7$ MEV for the K^{40} beta rays, in good agreement with the result obtained above.

Section 2. Particular Methods and Instruments.

The Beta Counter.

Fig. 18 shows the construction and dimensions of the G.M. tube used for beta counting. The cathode is of copper, polished with fine emery paper, and cleaned

Fig. 18



1. Shelf for sources
2. Shelf for absorbers

G.M. counter and source holder

before assembly with alcohol to remove all traces of grease. The tungsten anode wire had a nominal diameter of 0·2 mm., but this was reduced by about 10 per cent, during preliminary cleaning treatment with molten solium nitrite. The wire is partially shielded by the pyrex tube which supports it, in order to reduce the effective anode length to 2 cm. The reduction in the background count thus obtained is well worth the slight disadvantage of a corresponding diminution in the size of the pulses delivered by the counter. The pyrex bead at the end of the wire prevents spurious counts due to discharges from the point. External contact with the anode was made by placing a small amount of mercury in the glass tube, as shown.

The mica window, thickness 9·6 mg./cm.^{2}, is held firmly clamped between the flange and ring. These last were smeared with low vapour pressure grease before assembly, and the mica itself acted as gasket to provide a tight joint. The counter was pumped for four hours on black vacuum before filling to a pressure of 10 cm., with a 10 : 1 mixture of argon and alcohol. With the simple resistance quenching circuit used, the counter plateau extended for over 300 V from 1500 V, and the slope was less than 1 per cent per 100 V. The operating point was chosen as 1600 V, and here the background count was about 45/min. The counter was corrected for small day to day variations in sensitivity by making counts on a constant source consisting of a little powdered uraninite sealed into a brass holder with a thin layer of paraffin wax. No progressive change, however, was noted, either in the background count, or in the count from the uraninite source, during the five months the counter was in operation.

It would be presenting an unrealistic picture of the situation to close this description of the G.M. tube without referring to some of the difficulties encountered in its construction. Studies with a number of experimental tubes had first to be made in order to collect data on such subjects as the influence of cathode material and gas filling on counter performance, and the behaviour of thin mica windows. Cathodes of aluminium, brass, rhodium-plated brass, and copper, were investigated. Argon alcohol fillings to various pressures, and argon ether fillings were also tested. Collapse of the windows on evacuation was, however, the main source of trouble. As the window, when it ' exploded ', generally removed the anode wire as well, considerable time was lost due to this cause. Gentle heating of the flange while the retaining bolts were being carefully tightened, considerably increased the window's chance of survival. Rounding off of the inner lip of the flange, against which the window bore, (see fig. 18) also helped. Little trouble with breakage, or leaks through windows after filling, was experienced.

One instructive error occurred in the accidental filling of a counter with an air argon mixture from an almost exhausted argon cylinder. Alcohol was added as usual. Spurious pulses following the main ones, and due to electron attachment in air, were clearly visible on the oscilloscope screen.

The dimensions of the perspex stand used for supporting the sources and absorbers are also shown in fig. 18. It should be noted that (1) the ledge for the sources is close to the window (0·66 cm., away) for high geometry, and (2) the ledge for the

absorbers is only 0·37 cm., away from the window, resulting in negligible errors due to scattering. The small source to window distance also obviates errors due to differences in self-scattering between the relatively thick KCl, and the practically weightless RaE sources. One rather grave disadvantage with this arrangement was that the counter had to be lifted from the stand every time a source or absorber was changed, with a possibly deleterious effect on window life. However, no simple alternative arrangement which would give the same high geometry could be devised, on account of the rather large thickness of the clamping ring on the mica window. It was felt that any reduction of this thickness would only result in slight warping of the ring, and inevitable collapse of the window.

The whole counter was contained in a cubical lead box of internal dimensions 5 in. × 5 in. × 5 in., wall and floor thickness 1 in., and roof thickness $1\frac{3}{4}$ in., in order to reduce the background count from cosmic ray and other sources. The interior of the container was lined with 1/16 in., aluminium to eliminate the beta count from the lead itself. The unshielded count was at least 50 per cent greater than the count when shielded as described above.

Recording Mechanism.

The H.T. was applied directly to the anode of the counter, and the cathode run to earth through a 6·8 MΩ resistor. The resulting positive pulse at the cathode was inverted and amplified by an H63 triode, and fed into a scale of 16. The size of the pulses here was about 9 volts. The scale of 16 consisted of a soft valve scale of two followed by a similar scale of eight. The design of the latter followed closely that given by Strong (20) except that the thyratrons were type GTIC, the interstage triodes type MHL4, and the anode loads, except for the last stage, 10,000 Ω. The scale of two was of the same general nature (anode loads 5,000 Ω), but the time constants of the thyratron grid circuits were lengthened considerably. This was in order that the slow alpha pulses (~ 1/300 sec.), for which the same scaler was used, might not be severely attenuated. The RC constant of each circuit was increased from the 5×10^{-5} sec., of Strong's first pair to 2×10^{-4} sec. If the pulse passed on to the next stage is to be as sharp as possible, it is essential that the RC constant of the anode circuit should also be small. For stability, however, (RC) anode must be greater than (RC) grid, or else an extinguished thyratron will relight, leaving the scaler jammed with both thyratrons struck. We thus appear to be faced with two conflicting requirements.

Lewis (21) has shown that by placing cross connecting condensers between anode and grid, this dilemma may be avoided, and the anode time constant reduced below that of the grids. By this means a moderate performance was achieved, the magnitude of the counting losses occurring being discussed elsewhere in this paper. Naturally, all this trouble could have been avoided if the scaler was designed for fast geiger pulses only, for the grid time constants, and consequently those of the anode circuit, could then have been shortened considerably, and very sharp output pulses obtained without the necessity of cross linking condensers.

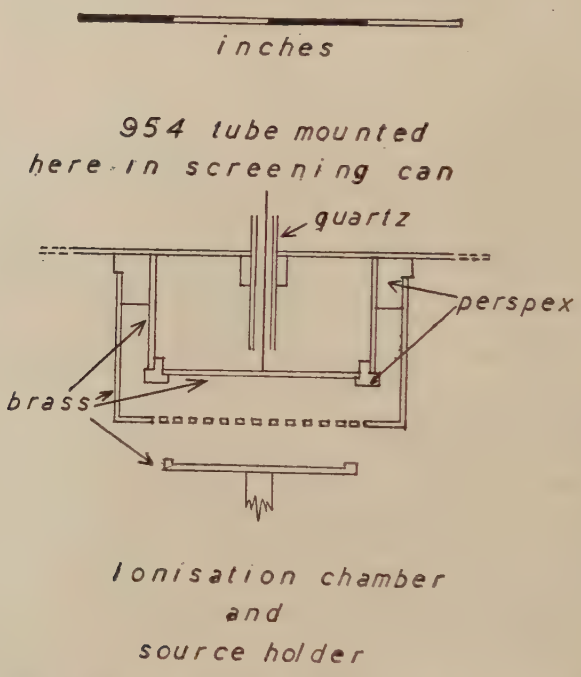
H.T. Power Supply.

The power supply for the G.M. counter was obtained from a 1000 V (R.M.S.) transformer and selenium rectifiers in a voltage doubling circuit. The voltage was stabilised using a degenerative arrangement similar to that suggested by Elmore and Sands (22). A stabilisation ratio of 30 : 1 was achieved, *i.e.*, a 30 per cent change in input voltage only produced a 1 per cent change in output voltage, and stabilised voltages of from 1400 to 2200 were obtainable.

The Alpha Counter.

A sketch of the alpha counter is shown in fig. 19. The chamber face is horizontal, and the sources are slid in underneath at a distance of 0·96 cm., away. This arrangement prevents the source falling off the backing in any case where it is in powder

Fig. 19



form. The perforated area has diameter 5·5 cm., which is substantially larger than the source diameter used (4·50 cm.). A positive voltage of 925 V is applied to the outer plate, and positive ions collected by the inner electrode. Sharper pulses would certainly have been obtained if electron collection was used, but this would have meant replacing the already available positive H.T. supply by a negative one. A connection from the collector electrode passes up through a quartz tube to the first stage of the amplifier. In a preliminary design this quartz tube was also used to

support the collector electrode. This method of suspension was found to have the disadvantage of not only allowing the electrode to be easily set into mechanical vibration, but also of making the insulation of the grid of the first amplifier tube too good, since its only other leakage path to earth was through the glass envelope of the tube itself. As a result of the latter, if a large negative pulse appeared at this grid due, say, to a fluctuation in the unstabilised H.T. supply to the chamber then during the minute or so it took for this charge to leak away again, no alpha pulses were recorded. The same cause produced strange effects in the shape of the alpha pulses themselves. The perspex insulation later introduced was found to eliminate this trouble, and by supporting the collector electrode at the rim rather than at the centre, it was made relatively insensitive to mechanical disturbances. The depth of the chamber was 1·2 cm.

The first amplifier stage consisted of a 954 tube connected in the manner described by Gabus and Pool (23). The normal suppressor grid, g_3, is used as a floating control grid, the normal screen grid, g_2, is held at from 9 to 12 volts, and the normal control grid, g_1, is anchored to the cathode. The use of g_3 as control grid is only possible because this valve is of all glass construction, and consequently all the electrodes are extremely well insulated.

The three main causes of grid current, (and hence noise) in a conventionally connected floating grid valve are (51) :—

(1) Positive ions formed by gas present in the tube,

(2) Cathode emission of positive ions, and

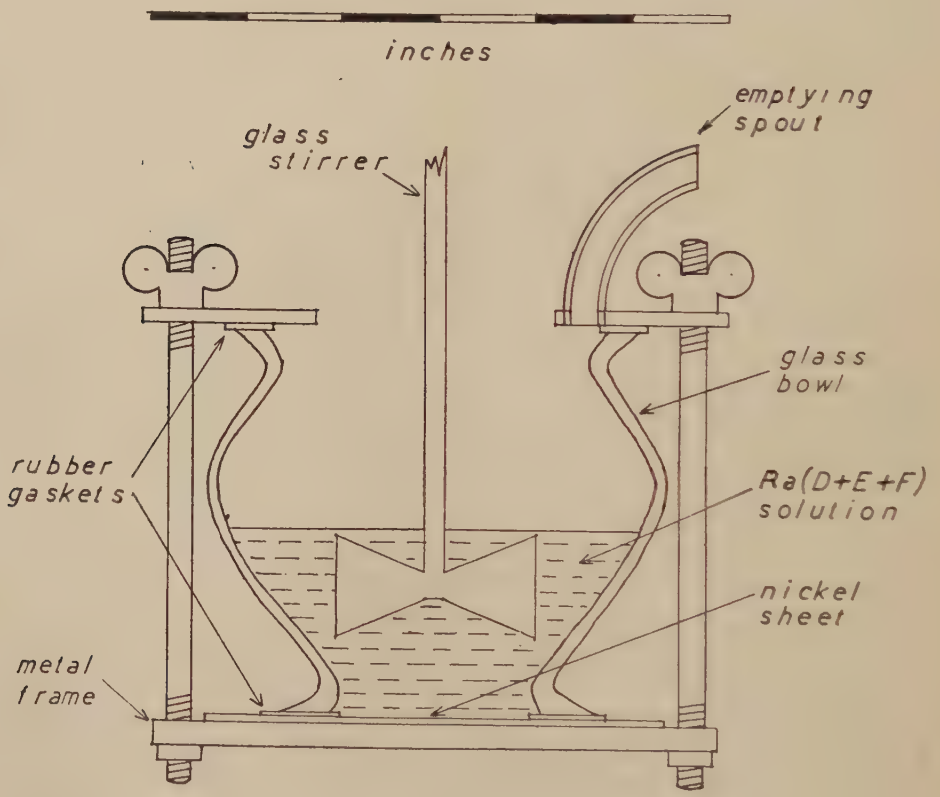
(3) Thermionic and photoelectric emission from the control grid.

Connected as above, however, the reduced anode and filament voltages practically eliminate causes (1) and (3), while positive ions from the cathode are blocked by the small positive voltage on g_2. (The common supply to this grid and the anode was originally 9 volts, but towards the end of the experiment, when the sensitivity of the counter, as judged by the count on the standard source, seemed to have decreased slightly, it was raised to 12 volts.) The function of g_1 is by no means clear, some authors (52) preferring to hold it at a small positive potential, ($\sim$ 1V), others (53) at a small negative potential of the same order. When connected directly to the cathode, as here, its main effect is probably to reduce the anode current somewhat, and thus the ionisation of the residual gas still further.

The remainder of the amplifier was orthodox in design, and consisted of three triode stages, followed by an output stage for driving an oscillograph if required. The final output to the scaler, with the whole gain not fully utilised, was from 6 to 9 volts for average alpha pulses. Since an ionisation chamber is not a trigger device like a G.M. counter, the pulse sizes depended on the path of the alpha particles in the chamber, and were therefore of varying magnitude from zero up to a certain maximum. The average signal to noise ratio was at least 10 to 1, which was ample for the rather high discriminator setting used on the scaler. The alpha counting efficiency of the whole arrangement as measured by comparison with the plate method

was 5·5 per cent. This low value is to be attributed, at least in part, to the form of the perforations of the anode plate through which the alpha particles passed into the chamber. Although the clear area in this comprised 47·2 per cent of the total, yet the transmission coefficient will be much less than this, since to avoid mechanical vibrations the disc was made fairly thick. In fact, the depth of each hole (1·58 mm.) was actually greater than its radius (1·4 mm.) This would be immaterial for a collimated stream of alphas, but leads to large losses for a non-parallel stream coming from a source held near the chamber. The high discriminator setting on the scaler helped in further reducing the efficiency. It must not be thought, however, that this rather low efficiency of counting had any adverse significance, since firstly, only a figure representative of the total alpha activity was required from the chamber, and secondly, quite a satisfactory count (from 100 to 200/min.) was registered by the average source even at this efficiency.

Fig. 20



Deposition apparatus

Preparation of Ra(E + F) sources.

As with other parts of this experiment, many preliminary trials and source preparations were made before a suitable technique was evolved, but only an example typical of the procedure finally adopted will be given. One discarded radon tube, about 14 days old, was crushed in a mortar in the open air, (to dissipate any radon remaining) and digested in N/10 HCl overnight. The resulting solution was found to be too strongly radioactive for convenient manipulation, and it was diluted in the ratio of 1 : 3·5, approximately. About 80 c.c., of this dilute solution were first placed in a large test tube, at room temperature, and stirred with a piece of nickel rotating at three to four revs./sec. for from one to two hours. This removed a large part of the RaF by spontaneous deposition, but also some RaE. Consequently, the liquid was left for a day or two to reform the latter. The volume was then doubled for convenience, and the apparatus shown in fig. 20 brought into operation.

In this, a piece of nickel rather larger than the final source size required, is clamped as shown between the steel disc and glass bowl. (The rather unusual shape of the latter, incidentally, has no special significance.) An upper brass ring anchored with four screwed rods holds the apparatus together, and the joints are made water-tight with rubber gaskets. The only cleaning of the nickel found necessary was a brisk rub with not too fine emery paper. The whole assembly was almost completely immersed in a water bath at 80° C., and the Ra (D + E + F) solution, after preliminary heating to the same temperature, transferred to the glass bowl. Here it was slowly stirred for about five minutes by a mechanical glass stirrer, during which time RaE, (but also a large part of the remaining RaF), was deposited. The nickel was then removed and a rough check on its alpha and beta activity made, the former with the ionisation chamber counter and the latter with the G.M. tube. As the beta count was relatively very large, a suitable reduction disc ($\div$ 8 approximately) had to be used. If the beta to alpha ratio was high enough, and the absolute values also suitable, the final circular source could be cut from the nickel sheet at once. If the beta to alpha ratio was high enough but the absolute value of each rather low, then the nickel sheet could be replaced in the deposition apparatus for, say, another $2\frac{1}{2}$ mins., and the activity further increased. If the beta to alpha ratio was too low, no matter what their absolute values, then the source was useless, and further preferential removal of RaF at room temperature was necessary.

The relevant information regarding the scanning of the plates by microscope after development has already been given in the main text, and will not be discussed further here.

SECTION 3. ESTIMATION OF ERRORS, COMPARISON OF RESULTS WITH THOSE OBTAINED BY OTHER WORKERS, AND SURVEY OF PROPOSED DECAY SCHEMES FOR K^{40}.

Estimation of Errors.

We will first estimate the error in the value given for the specific beta activity. This is contributed to by the following terms :—

1. Error in the estimated efficiency of the G.M. counter. Let us first assume that the four values obtained for the efficiency are distributed in a perfectly random manner. Then, with the usual notation, the

probable error $= a = 0{\cdot}6745\sqrt{\frac{\Sigma d^2}{n(n-1)}}$

Since two of the readings are weighted twice as heavily as the others, we have really six values, 27·54 (S. 17), 31·81 (S. 18), 30·72 (S. 19), twice, and 28·83 (S. 20), twice.

Forming the difference from the mean, 29·74, and substituting, we get,

$$a = 0{\cdot}6745\sqrt{\frac{12{\cdot}70}{6 \times 5}} = 0{\cdot}4387.$$

The percentage error is thus $\frac{0{\cdot}4387 \times 100}{29{\cdot}74} =$ 1·48%

2. Besides purely random errors in the determination of the efficiency, we have the possible systematic errors in the area of the microscope field. By means of a standard scale, the diameter was estimated to be

$2{\cdot}875 \pm 0{\cdot}02 \times 10^{-2}$cm., *i.e.*, error in *area* $= \frac{0{\cdot}02}{2{\cdot}875} \times 2 \times 100 =$ 1·39%

3. A similar possible error occurs in the area of the source. Here the diameter is $4{\cdot}50 \pm 0{\cdot}01$ cm., *i.e.*, the probable error in the area is

$$\frac{0{\cdot}01}{4{\cdot}50} \times 2 \times 100 =$$ 0·44%

4. The efficiency of the plates is given by $50{\cdot}2 \pm 0{\cdot}1\%$, *i.e.*, the probable error is $\frac{0{\cdot}1 \times 100}{50{\cdot}2} =$ 0·20%

5. Error in the extrapolated value for the observed count/gm. of KCl. It is estimated from the lie of the points on fig 13 that the true value of the logarithm of the extrapolated count could not lie outside the values 2·50, and 2·52, with the logarithm of the true value estimated at 2·51. These numbers correspond to actual values of 316·2, 331·1 with an estimated true value ot 323·6.

The probable error is therefore $\frac{7{\cdot}5 \times 100}{323{\cdot}6} =$ 2·32%

6. In a similar manner by direct estimation from fig. 11, it is clear that the limits for the logarithm of the window absorption factor for RaE

are 0·07 and 0·09, with the logarithm of the true value estimated at 0·08. These correspond to factors of 1·175, 1·230, and 1·202, with a probable

error of $\frac{0{\cdot}028}{1{\cdot}202} \times 100 =$ 2·33%

7. For the error in the window absorption factor for $K,^{40}$ the corresponding values of the logarithms are 0·040, 0·050, and 0·045, and of the factors themselves 1·096, 1·122, and 1·109, (fig. 12). The probable error is

thus $\frac{0{\cdot}013}{1{\cdot}109} \times 100 =$ 1·17%

The total error in the value for the specific beta activity is thus, 9·3(3)%

i.e., actual error $= \frac{31{\cdot}89 \times 9{\cdot}33}{100} = 2{\cdot}977$

i.e., specific beta activity of potassium $= 31{\cdot}9 \pm 3$ betas/sec.

(The total probable error as found above is almost certainly an overestimate, since many of the individual errors could be more properly described as 'maximum' rather than 'probable' errors.)

The uncertainty in the values previously given (page 271) for the beta decay constant and half life of K^{40} will be approximately 10 per cent, since Nier (11) claims an accuracy of one part in 119 for his latest determination of the isotopic constitution of potassium.

It is interesting, for the sake of comparison with other workers' results, to estimate the error in the determination of the counter geometry alone. This is made up of errors discussed in paragraphs 1, 2, 3, 4, and 6 above,

and = 5·8(4)%

This is in good agreement with the results of Burtt, (5) who feels that a figure of 6 per cent or less, is a reasonable one for the error in estimating counter geometry. Those claiming values to $\pm$ 2%, are, he states, being 'over-optimistic'.

The probable error in the value of 69·5 mg./cm.^{2} for the half thickness in aluminium for the beta rays of K^{40} is $\pm$ 2 mg./cm.^{2}, this being estimated directly from the graph of fig. 16. The question of error in the value of 1·65 MEV for the maximum beta energy deduced from Mlle. Perey's formula has already been discussed elsewhere in this paper (page 277).

Comparison of Results with those of Other Workers.

The following is a synopsis of other determinations of the specific beta activity of potassium.

Author(s)	Ref.	Year	Specific Activity		Method
Muhlhoff	24	1930	(23·3)	×	Thin-walled counter. U + UX calibration. K salt on brass. No correction for back-scattering.
Bleuler and Gabriel	25	1947	(53·7 ± 7·7)	×	Thin-walled counter. Calculation of geometry. K salt on brass. No correction for backscattering.
Ahrens and Evans	26	1948	34 ± 5·2	√	This figure merely estimated from a consideration of the errors due to backscattering in the previous two results (24 & 25). No actual determination made.
Graf	27	1948	26·8 ± 1·2	×	Thin-walled counter (27mg./cm.^{2}). UX_2 calibration. Source on 1·9 mg. cm.^{2} Al., hence no backscattering.
Borst and Floyd (I)	16	1948	(21·4 ± 2·2)	×	Mica end-window counter. UX_2 and RaE—RaF calibration. Source on 7 mg./cm.^{2} Al., and backscattering stated to be negligible. Just one KCl sample (2·5 mg./cm.^{2}), enriched 14 fold in K^{40}, used.
Hirzel and Waffler	15	1948	(33·5 ± 5·7)	√	Thin-walled counter (27 mg./cm.^{2}) U_3O_8 calibration. Source on 2·7 mg./cm.^{2}, backscattering determined to be less than 1 per cent. Just one sample (4 mg./cm.^{2}), used.
Borst and Floyd (II)	17	1949	(23·1 ± 2·1 (5))	×	Same as previous work by same authors (ref. 16). Just one KCl sample (6 mg./cm.^{2}), enriched 100 fold in K^{40}, used.

Author(s)	Ref.	Year	Specific Activity		Method
Stout	28	1949	$30{\cdot}6 \pm 2{\cdot}0$	√	Mica end-window counter (2·7 mg./cm.^{2}) Activity of K compared with Na^{24}, which was calibrated by gammas from a Co^{60} standard. Since Na^{24} and K^{40} spectra identical (see ref. 15), all corrections eliminated.
Spiers	29	1950	$30{\cdot}5$	√	Metal end-window counter (6 mg./cm.^{2}) Internal calibration with Na^{24}, as in previous reference, (28).
Faust	30	1950	$31{\cdot}2 \pm 3{\cdot}0$	√	Counters immersed in a large tank of KCl solution. Calculation of geometry involving the mean range of K^{40} betas in water, deduced from Alburger's figures (ref. 35). Result checked with known Na^{24} source.
Sawyer and Wiedenbeck	31	1950	$28{\cdot}3 \pm 1{\cdot}0$	√	Special 4π counter, with internal KCl source.
Smaller, May and Freedman	32	1950	$(22{\cdot}5 \pm 0{\cdot}7)$	×	Scintillations in KI crystals, detected with photomultiplier tubes.
Present Author	—	1950	$31{\cdot}9 \pm 3$		Mica end-window counter (9·6 mg./cm.^{2}) Ra (E + F) calibration using nuclear plates. Backscattering automatically compensated for.

The figures in brackets are for those cases where the authors gave either the disintegration constant or the half life, but not the specific activity directly. This has been calculated for purposes of comparison, using the old value (1) of the abundance of K^{40} ($0{\cdot}011 \pm 0{\cdot}001\%$), as being the one available to the authors at the time. The new value (11), ($0{\cdot}0119 \pm 0{\cdot}0001$) was not published by Nier until March, 1950. Smaller, May, and Freedman gave their result as the number of disintegrations

/min./gm., of Kl, and the bracket round their figure merely indicates that this has been converted into betas/sec./gm., of ordinary potassium.

The ticks indicate those values with which the present result is in agreement within the limits of experimental error quoted, the crosses those which do not agree with it.

A grand average of all the above results yields a value of 30·1 betas/sec./gm., for the specific activity, with the uncertainty probably better than ± 1.

Determination of the Maximum Beta Energy of K^{40}.

Author(s)	Ref.	Year	$E_{max.}$ (MEV).	Method
Dzelepow, Kopjova and Vorobjov	33	1946	1·35 ± 0·05	Magnetic spectrometer with coincidence counting arrangement.
Franchetti and Giovanozzi	34	1948	1·7 ± 0·1	Cloud chamber and Fermi plot. They find that only 1 per cent of the betas have energy greater than 1·4 MEV.
Borst and Floyd (I)	16	1948	1·9 ± 0·2	Absorption in aluminium using end window counter. Feather plot. Enriched K, (14 fold.)
Hirzel and Waffler	15	1948	1·41 ± 0·02	Absorption in aluminium using thin-walled counter. K^{40} and Na^{24} spectra found to be identical.
Borst and Floyd (II)	17	1949	1·45 ± 0·15	Absorption in aluminium using end-window counter, as before. 100 fold enriched K.
Alburger (I)	35	1949	1·40 ± 0·03	Magnetic spectrometer and Fermi plot. 100 fold enriched K. (1·2% K^{40}).
Bell, Weaver and Cassidy	36	1950	1·36 ± 0·05	Scintillation spectrometer and Kurie plot. Enriched K, (1·31 ± 0·05% K^{40}).
Alburger (II)	37	1950	1·36 ± 0·03	Magnetic spectrometer and Kurie plot. Enriched K, (7·13% K^{40}).

Author(s)	Ref.	Year	$E_{max.}$ (MEV).	Method
Smaller, May and Freedman	32	1950	$1{\cdot}3 \pm 0{\cdot}1$	Scintillations in KI crystals. Pulse height measurements, calibrated with Cs^{137} betas.
Present Author	—	1950	$1{\cdot}65 \pm 0{\cdot}2$	Determination of half thickness in aluminium with end-window counter, and use of Perey formula.

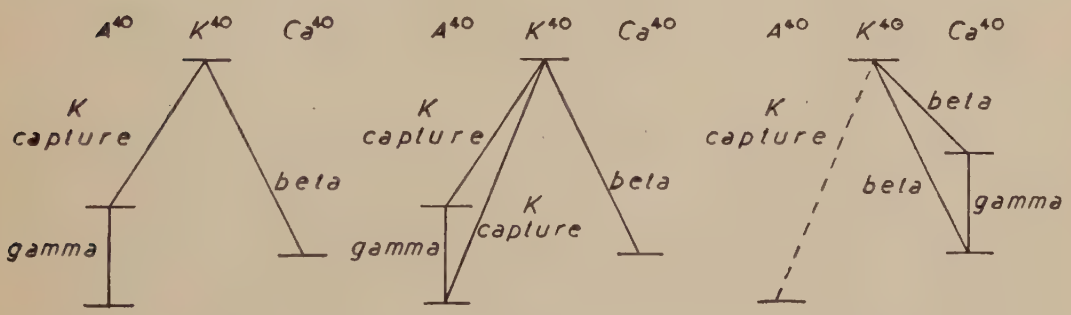
A grand average here yields 1·49 MEV, but this unweighted figure is of rather doubtful significance.

Decay Schemes.

K^{40} is known to decay with the emission of beta and gamma rays. The beta ray emission implies Ca^{40} as the product nucleus, and the gamma ray is usually associated with a K capture transformation (2) to A^{40}. Important, but indirect evidence for the latter is that the atmospheric A^{40} is believed to have come almost entirely from K^{40}, A^{36} being cosmically the most abundant isotope (38) of argon. The number of gammas per 100 betas has been variously estimated (39) at from 5 to 15.

Three distinct types of decay scheme have been either proposed or implied, and they are shown below over the names of their respective supporters.

Fig. 21



Sawyer and Wiedenbeck(31).

Suess (40).

Bleuler and Gabriel (25).

Gleditsch and Graf (41).
Ahrens and Evans (26).
Graf (42).

Franchetti and Giovanozzi (34).

The first fact to be noted is that only if $E_{max.}$ beta is greater than E gamma ($\sim 1{\cdot}5$ MEV) (15, 41) can the gamma ray be emitted in cascade with the beta ray. Although Borst and Floyd's first value (16) of $1{\cdot}9$ MEV for $E_{max.}$ beta permits of such a disintegration sequence, they do not make any reference to it in their paper. Franchetti and Giovanozzi, however, who obtained a value of $1{\cdot}7$ MEV for the same quantity, (34) discuss the possibility of this process, and point out that if it is in fact taking place, then there should be a weak band in the beta spectrum with an end point at $E_{max.}$, beta $-$ E gamma $= 1{\cdot}7 \pm 0{\cdot}1 - 1{\cdot}5$ MEV $= 0{\cdot}2 \pm 0{\cdot}1$ MEV. They state that Bocciarelli (43), using a magnetic deflection method, did indeed find an inflection at $H\varrho = 1300$ (*i.e.*, $0{\cdot}13$ MEV), which was just above statistical errors.

If this hypothesis is assumed, then the decay scheme will look as shown in (C). Some beta rays will decay directly to the ground state of Ca^{40}, others to an exicited state, and to ground with gamma ray emission. It is to these latter betas that the band in the beta spectrum previously mentioned, corresponds. Decay by K capture to the ground state of A^{40}, without emission of a gamma ray, is not of course debarred, and this transition is shown dotted.

The difficulty with this scheme is as follows :—

Meyer, Schwachheim, and de Souza Santos (44) searched directly for beta gamma coincidences, and found none to an accuracy of 1 per cent. This means that the gamma beta ratio can not be greater than this figure. A ratio of this order appears very unlikely in the light of the larger results of from 5 to 15 per cent obtained by many other workers (39). We might try assuming, as a last resort to make the scheme work, that gammas are emitted in both the K^{40} to Ca^{40}, and K^{40} to A^{40} transitions, but this type of *ad hoc* assumption is extremely distasteful on general grounds. We must, then, dismiss the proposed scheme as extremely improbable, but naturally the observational value of $1{\cdot}7$ MEV for the maximum beta energy is not thereby invalidated.

We turn, therefore, to the possibility of K capture to an excited nuclear state of A^{40} to provide the gamma rays observed. This is indicated in schemes (A) and (B). If the number of K captures can be shown to be equal to the number of gamma rays emitted, then scheme (A) is correct, while if the number of K captures exceeds the number of gamma rays, then there must exist, in addition, K capture to the ground state of A^{40} without gamma ray emission, as indicated in scheme (B). In both cases, however, there will be X-ray emission due to electronic rearrangement.

The critical constant to be determined then, is the branching ratio λ_e/λ_β— the ratio of electron captures to beta emissions, and this is to be compared with the experimentally determined gamma/beta ratio, 5 to 15 per cent. Bleuler and Gabriel (25) obtained a value of $1{\cdot}9 \pm 0{\cdot}4$ for the branching ratio, by absorption of the X-rays from K capture in argon and carbon tetrachloride mixtures. These workers' original paper was not available to the writer, but Ahrens and Evans state that

their value of the branching ratio was based on a change of only three counts per minute against a background of 180 counts per minute due to the K^{40} beta particles—a very unsatisfactory state of affairs.

Ahrens and Evans' own figure (26), based on studies of the Ca^{40}/K^{40} ratio in $2{\cdot}1 \times 10^9$ year-old minerals is $1{\cdot}4 \pm 0{\cdot}2$.

From his own figures on beta ray emission, and examination of Bleuler and Gabriel's and Ahrens and Evans' results, Graf concludes (27, 42) in successive communications that the value for the branching ratio should be $1{\cdot}8 \pm 0{\cdot}5$ and $2{\cdot}45 \pm 0{\cdot}5$. Later, deducing the number of K captures directly, by detecting the X-rays in turn in counter fillings having poor and high sensitivity for the K_α rays of argon (4·18 A), he found (45) a value for the branching ratio of $0{\cdot}67 \pm 0{\cdot}20$. This, he adds, should be considered an upper limit. The same criticism may be levelled at Graf's work as at Bleuler and Gabriel's, for here also the figure for the branching ratio depended on a very small change in count, actually about 2 per cent.

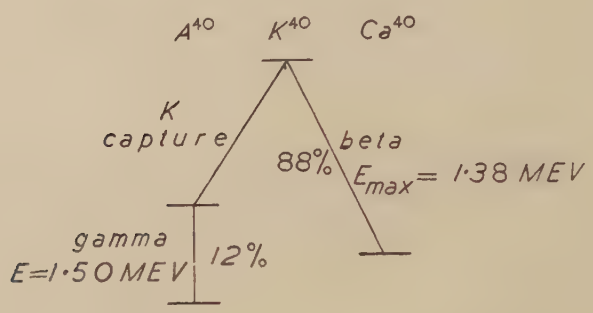
Borst and Floyd (16), made measurements on the argon content of a sylvite sample in an attempt to determine the branching ratio, but found that on account of the possibility of losses of A^{40} from the mineral, and of contaminants in the extracted gas, they could only place it in the range 0·5 to 3.

Any of the previous ratios quoted will automatically necessitate the adoption of scheme (B), since the number of K captures far exceeds the number of gammas. Suess (40), however, from an examination of the argon content of sylvine and carnalite specimens, and from general geophysical considerations, concluded that a branching ratio much greater than 0·1 was unlikely. (Later work by Aldrich and Nier (46) on the A^{40}/A^{36} ratio in potassium minerals, and by Ceccarelli, Quareni, and Rostagni (47) on the direct determination of λ_e/λ_β confirmed this view.) He, therefore, suggested a scheme like (A), with 5 ± 2 gammas (and therefore 5 K captures) per 100 betas. At the time of writing his paper, the authenticity of Bleuler and Gabriel's data on the number of X-rays emitted per gm. of potassium had not been questioned, and consequently Suess felt obliged to associate about 200 X-rays in some way with every 100 beta disintegrations to Ca^{40}.

Even this difficulty was removed a considerable time later by the work of Sawyer and Wiedenbeck (31). These authors determined directly, (1) the specific gamma activity, (2) the specific beta activity with an internal sample counter, and (3) the percentage of K captures, by detecting the Auger electrons into which 88 per cent of the X-rays are converted. For this they used a special screen grid counter which differentiated between Auger electrons and ordinary beta rays. They thus had at their disposal all the data necessary to deduce the branching ratio, without drawing on any results of other workers. They found, that within the still large limits of error, ($\sim 30\%$), in determining the number of K captures, the number of these equals the number of gammas emitted, and represent approximately 12 per cent of the

total activity. The beta disintegration to Ca^{40} make up the remaining 88 per cent, the branching ratio becomes $12/88 = 0{\cdot}135$, and the final scheme as given by these workers takes the form shown below.

Fig. 22



In assessing the relative merits of the various proposals, one cannot but help being struck with the care and completeness with which Sawyer and Wiedenbeck made their investigations, and apart from small modifications in numerical values, one feels that their proposed scheme is indeed the correct one.

One further interesting possibility ought to be briefly mentioned. In a private discussion, Professor Poole made the suggestion that many conflicting results might be correlated, if K^{40} were assumed to consist of two nuclear isomers decaying independently by beta emission and K capture. Many such nuclear isomers are now known, mostly indeed decaying by electron capture and positron emission, but there seems no valid reason why beta ray emission and K capture should not go together. Although the decay scheme for Au^{196} is not yet perfectly definite, it, for example, probably decays in this way (48). Nuclear isomers are normally detected by the fact that the ratio of the amounts of decay products present (A^{40} and Ca^{40} in this case) does not remain constant with time. Since K^{40} has such a long half life, a direct verification is naturally impossible. It is to be noted, however, that Inghram, Brown, Patterson, and Hess (49) found that the relative amounts of A^{40} and Ca^{40} in a sylvite mineral of age 10^8 years yielded a branching ratio of $0{\cdot}126 \pm 4\%$, which is to be compared with the value of Sawyer and Wiedenbeck of $0{\cdot}135$, taken with ordinary potassium. Owing to the magnitude of the error involved in both measurements, it is difficult to say whether this apparent decrease in the branching ratio has any real significance. A decrease of approximately double that obtained would be required on the isomer theory, with the numerical values given below. It must be remembered also, that 10^8 years is quite a short period on the geological scale—less than one tenth of the total half life of potassium, and similar work on older rocks should yield more definite results.

It can be shown (50) that the isomer theory can reconcile the data of Sawyer and Wiedenbeck, Ahrens and Evans, Aldrich and Nier, and Inghram and his co-workers, to within the limits of experimental error, if we assume :—

$$\lambda_e = 8{\cdot}9 \times 10^{-11} \text{ yrs.}^{-1}$$
$$\lambda_\beta = 1{\cdot}75 \times 10^{-9} \text{ yrs.}^{-1}$$
$$\text{and } \frac{n_\beta}{n_e} = \text{relative abundance of the two isomers in } K^{40},$$
$$= 0{\cdot}40$$

On the single parent theory, Ahrens and Evans' results are absolutely irreconcilable with the other data. Neither theory, however, satisfactorily explains numerically the large A^{40} content of the atmosphere, if this is supposed to have come entirely from the K^{40} in the crust.

SUMMARY.

The beta activity of potassium due to its isotope of mass 40 has been investigated using an end window Geiger Muller counter. The geometry of the counter was first determined to be 35·8 per cent by measuring the apparent beta emission from standard Ra(E + F) sources. The absolute activity of these sources had previously been deduced from alpha particle counting with nuclear plates. It was not necessary to correct this figure of 35·8 per cent for beta particle backscattering, since nickel of sufficient thickness to give saturation backscattering was used as backing for all sources, both Ra E and KCl.

Counts on KCl sources, extrapolated to zero thickness, gave a result of 5·39 betas/sec./gm. of KCl, at the above geometry. This, when corrected for counter window absorption, yields a value of 31·9 ± 3 betas/sec./gm. of ordinary potassium. The corresponding values for the disintegration constant and half life for beta decay of K^{40} are then $5{\cdot}5 \times 10^{-10}$ yrs.$^{-1}$, and $1{\cdot}25 \times 10^{9}$ yrs., respectively, the probable error in each case being approximately 10 per cent.

The half thickness for the K^{40} beta rays, that is, the thickness of aluminium required to reduce their intensity by half, was also determined, and found to be 69·5 ± 2 mg./cm.^{2} Using a relation due to Perey, this leads to a maximum beta energy of 1·65 ± 0·2 MEV.

The paper concludes with a critical survey of the results of other workers, and of the various decay schemes which have been proposed for K^{40}.

BIBLIOGRAPHY.

(1) NIER.—*Phys. Rev.*, **50**, 1041, (1936).
(2) V. WEIZSACKER.—*Physik. Zeits.*, **38**, 263, (1937).
See also for example, refs. 25 and 31.
(3) CURRAN AND CRAGGS.—' Counting Tubes '. (*Butterworth*), p. 83.
(4) MME. JOLIOT CURIE.—' Les Radioelements Naturels ', (*Hermann & Cie.*) p. 89.
(5) BURTT.—Nucleonics, **5**, 28, August (1949).
(6) ROSSI AND STAUB.—' Ionisation chambers and counters ', (*McGraw Hill*), Pp. 127, 240.
(7) ZUMWALT, MDDC, 1346.

(8) Engelkemeier, Seiler, Steinberg, Winsbert, and Novey.—*Plutonium Project Record*, **9B**, 2.4.
(9) Tobias.—' Handbook of Radioactivity and Tracer Methodology ' Pp. 473—496.
(10) Wu, Meaker, and Glassford.—*Rev. Sci. Instr.*, **18**, 693, (1947).
(11) Nier.—*Phys. Rev.*, **77**, 789, (1950).
(12) Curran and Craggs.—as above, p. 89.
(13) Blachman.—Quoted by Burtt, see ref. 5.
(14) Feather.—*Proc. Camb. Phil. Soc.*, **34**, 599, (1938).
(15) Hirzel and Waffler.—*Phys. Rev.*, **74**, 1553, (1948).
(16) Borst and Floyd.—*Phys. Rev.*, **74**, 989, (1948).
(17) Borst and Floyd.—*Phys. Rev.*, **75**, 1106, (1949).
(18) Mlle. Perey, J.—*Phys.*, **6**, 28, (1945).
(19) Mme. Joliot Curie.—As above, p. 181.
(20) Strong.—' Modern Physical Laboratory Practice ', (*Blackie*), p. 288.
(21) Lewis.—' Electrical Counting ', (*Cambridge University Press*), p. 83.
(22) Elmore and Sands.—' Electronics ', (*McGraw Hill*), p. 382.
(23) Gabus and Pool.—*Rev. Sci. Instr.*, **8**, 196, (1937).
(24) Muhlhoff, Ann.—*d. Physik.*, **7**, 205, (1930).
(25) Bleuler and Gabriel.—*Helv. Phys. Acta*, **20**, 67, (1947).
(26) Ahrens and Evans.—*Phys. Rev.*, **74**, 279, (1948).
(27) Graf.—*Phys. Rev.*, **74**, 831, (1948).
(28) Stout.—*Phys. Rev.*, **75**, 1107, (1949).
(29) Spiers.—*Nature*, **165**, 356, (1950).
(30) Faust.—*Phys. Rev.*, **78**, 624, (1950).
(31) Sawyer and Wiedenbeck.—*Phys. Revs.*, **79**, 490, (1950).
(32) Smaller, May and Freedman.—*Phys. Rev.*, **79**, 940, (1950).
(33) Dzelepow, Kopjova, and Vorobjov.—*Phys. Rev.*, **69**, 538, (1946).
(34) Franchetti and Giovanozzi.—*Phys. Rev.*, **74**, 102, (1948).
(35) Alburger.—*Phys. Rev.*, **75**, 1442, (1949).
(36) Bell, Weaver, and Cassidy.—*Phys. Rev.*, **77**, 399, (1950).
(37) Alburger.—*Phys. Rev.*, **78**, 629, (1950).
(38) Brown.—*Rev. Mod. Phys.*, **21**, 625, (1949).
(39) See for example, the following references, 15, 29, 30, 31, and 32.
(40) Suess.—*Phys. Rev.*, **73**, 1209, (1948).
(41) Gleditsch and Graf.—*Phys. Rev.*, **72**, 640, (1947).
(42) Graf.—*Phys. Rev.*, **74**, 1199, (1948).
(43) Bocciarelli.—*Rend. Acc. Linc.*, **15**, 686, (1932).
(44) Meyer, Schwachheim, and de Souza Santos.—*Phys. Rev.*, **71**, 908, (1947).
(45) Graf.—*Phys. Rev.*, **79**, 1014, (1950).
(46) Aldrich and Nier.—*Phys. Rev.*, **74**, 876, (1948).
(47) Ceccarelli, Quareni and Rostagni.—*Phys. Rev.*, **80**, 909, (1950).
(48) General Electric Research Laboratory.—Chart of the Nuclides, (1950).
(49) Inghram, Brown, Patterson and Hess.—*Phys. Rev.*, **80**, 916, (1950).
(50) Poole and Delaney.—*Nature*, (to be published).
(51) Metcalf and Thompson.—*Phys. Rev.*, **36**, 1489, (1930).
(52) Nielsen.—*Rev. Sci. Instr.*, **18**, 18, (1947).
(53) Prescott.—*Rev. Sci. Instr.*, **20**, 553, (1949).
(54) Cook, Duncan, and Hewitt.—*Nucleonics*, **8**, 24, January, (1951).